WASP - A FLEXIBLE FORTRAN IV
COMPUTER CODE FOR CALCULATING
WATER AND STEAM PROPERTIES

by Robert C. Hendricks, Ildiko C. Peller,
and Anne K. Baron

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SUMMARY
A FORTRAN IV subprogram, WASP, was developed to calculate the thermodynamic and transport properties of water and steam. The temperature range is from the triple point to 1750 K, and the pressure range is from 0.1 to 100 MN/m$^2$ (1 to 1000 bars) for the thermodynamic properties and to 50 MN/m$^2$ (500 bars) for thermal conductivity and to 80 MN/m$^2$ (800 bars) for viscosity. WASP accepts any two of pressure, temperature, and density as input conditions. In addition, pressure and either entropy or enthalpy are also allowable input variables. This flexibility is especially useful in cycle analysis. The properties available in any combination as output include temperature, density, pressure, entropy, enthalpy, specific heats ($C_p$ and $C_v$), sonic velocity, $(\partial P/\partial \rho)_T$, $(\partial P/\partial T)_\rho$, viscosity, thermal conductivity, surface tension, and the Laplace constant.

The subroutine structure is modular so that the user can choose only those subroutines necessary to his calculations. Metastable calculations can also be made by using WASP.

INTRODUCTION
Water is inert, inexpensive, and available. It is used for cooling equipment, for heating or cooling other fluids, as a modeling fluid, and in many cases as the primary test fluid in heat-transfer and fluid dynamics research.

Printed tables of water and steam properties have been available to the engineer for many years, the latest accepted editions being references 1 and 2. Numerous computer codes to interpolate these tables using a variety of curve-fit and interpolation techniques are available. Many are cumbersome or lack the ability to calculate a consistent set of properties for a given point in the fluid surface. Some are designed for specific uses and do not include all the properties. A comprehensive, flexible, and internally consistent computer code for water properties was needed at the Lewis Research Center.
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In determining the coefficients of equation (1), the temperature data were all expressed on the thermodynamic Celsius temperature scale. Since experimental observations for water, however, are usually reported in terms of the International Practical Scale (the I. P. Scale), a lengthy discussion and a graph of the relation between the I. P. Scale and the thermodynamic temperature scale are presented in reference 3.\(^2\)

The critical constants of reference 3 differ from those presented in references 1 and 2 as follows:

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The temperatures in this table are on the I. P. Scale. The critical temperature \(T_c\) of reference 3 on the thermodynamic scale is 374.136 °C.

The WASP subprogram was developed to be used in fluid-flow and heat-transfer calculations. There are independent calls for obtaining any one of the three state variables (pressure, density, and temperature) as a function of the other two (see table I, OPERATIONS SHEET FOR SUBROUTINE WASP). In addition, temperature and all the other properties can be obtained as a function of pressure and enthalpy (or pressure and entropy). This option is of considerable value in forced-convection studies and cycle analysis.

While enthalpy, entropy, and specific heats \((C_p \text{ and } C_v)\) are available in reference 3, the sonic velocity, viscosity, thermal conductivity, and surface tension were not computed in reference 3. The sonic velocity, equation (B30), is defined in terms of equation (1). The transport properties are discussed in the following section.

**TRANSPORT PROPERTY CALCULATIONS**

The thermal conductivity, viscosity, and surface tension are available in references...

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16. Abstract 
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WASP is a FORTRAN IV subprogram developed for engineering calculations. The thermodynamic properties are calculated by using the Helmholtz free-energy equation developed by Keyes, Keenan, Hill, and Moore (ref. 3). The transport properties are calculated by using curve fits given in references 1 and 2 in regions where these equations exist. The authors developed their own approximations based on the tabulated values of references 1 and 2 where curve fits were not available.

The main section of this report is directed to the research-oriented user of WASP. It includes a brief discussion of the equations used in calculating thermodynamic and transport properties. Comparisons to the International Skeleton Tables and the validity of transport calculations are also discussed. A detailed presentation of user instructions is included together with a tabular summary for later reference. Detailed information about the computer program and the equations used are included as appendixes. The symbols are defined in appendix A; the property equations of WASP are given in appendix B; the important subroutines of WASP are described in appendix C; the modular design of WASP is presented in appendix D; the program listing and flow chart are presented in appendix E, the test program output in appendix F, the metastable subroutine PMETAS in appendix G, and the thermodynamic relations and derivatives in appendix H.

**THERMODYNAMIC CALCULATIONS**

Keyes, Keenan, Hill, and Moore (ref. 3) fit the available experimental water and steam data from the triple point to a pressure of 100 MN/m² and to a temperature of about 1750 K, using the fundamental equation

\[ \psi = \psi(T, \rho) \]

\[ = \psi_0(T) + RT[\ln \rho + \rho Q(\rho, \tau)] \]  

(1)

where \( \psi \) is the specific Helmholtz free energy and \( \tau = 1000/T \). The specific forms of \( \psi_0(T), Q(\rho, \tau), \) and the derivatives of \( Q(\rho, \tau) \) are presented in appendix B.

Most investigators (e.g., refs. 4 to 7), in order to represent their measured values as closely as possible, have selected a modified virial equation of state

\[ P = P(T, \rho) \]

\[ = \sum_{i=1}^{6} A_i(T)\rho^i + \sum_{j=1}^{2} B_j(T)\rho^{2j+1} e^{-c\rho^2} \]  

(2)
where \( P \) is the pressure and the coefficients \( A_i(T) \) and \( B_j(T) \) are usually polynomials in \( T \) and \( T^{-1} \).

While the derivation of pressure from equation (1) is quite simple,

\[
P = \rho^2 \left( \frac{\partial \psi}{\partial \rho} \right)_T
\]

\[
= \rho RT \left( 1 + \rho Q + \rho^2 \frac{\partial Q}{\partial \rho} \right)
\]

the ensuing expanded descriptions for both equations (2) and (3) are quite involved, see appendix B and reference 8.

One should note the influence of the modified forms of the Benedict-Webb-Rubin (BWR) equation of state (see refs. 4 to 6) and the more recent work of Bender (ref. 7) on equation (1). (Compare the form of \( Q \) in eq. (B4) of appendix B with eq. (2).) The authors of references 5 and 6 added new exponential terms to the BWR equation of reference 4 to account for high-density effects. The technique has been successfully applied to several cryogens. More recently, Bender (ref. 7), in addition to these modifications, imposed another constraint, namely that the Maxwell Phase Rule must be satisfied; the constraint requires that the Gibbs free energy for the saturation liquid and vapor be equal. This latter constraint, although not stated explicitly, is implicitly satisfied by equation (1) (taken from ref. 3) because the Gibbs free energy of the saturated liquid and vapor are "virtually identical."

Both equations (1) and (2) have been fit by using a weighted least-squares technique which minimizes the residuals in pressure subject to various constraints such as

\[
\left( \frac{\partial^2 P}{\partial \rho} \right)_T = 0 \quad \left( \frac{\partial^2 P}{\partial \rho^2} \right)_T = 0 \quad \rho = \rho_c \quad T = T_c
\]

at the thermodynamic critical point. Reference 3 cites 14 such constraints; usually, the number is about one-half as many. However, the advantage of the reference 3 approach is that \( \psi \) as a function of \( \rho \) and \( T \) is a fundamental equation and all thermodynamic properties are obtained directly from \( \psi \) and its derivatives. In equation (2), \( P \) as a function of \( \rho \) and \( T \) is a state equation. In determining properties such as enthalpy, entropy, and specific heats, the state equation must be differentiated and integrated and the associated constants of integration must be determined from other data.\(^1\)

\(^1\) The mathematical form of the derived and integrated equations must be such that they do not possess singularities except at the critical point.
In determining the coefficients of equation (1), the temperature data were all expressed on the thermodynamic Celsius temperature scale. Since experimental observations for water, however, are usually reported in terms of the International Practical Scale (the I. P. Scale), a lengthy discussion and a graph of the relation between the I. P. Scale and the thermodynamic temperature scale are presented in reference 3.  

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While enthalpy, entropy, and specific heats ($C_p$ and $C_v$) are available in reference 3, the sonic velocity, viscosity, thermal conductivity, and surface tension were not computed in reference 3. The sonic velocity, equation (B30), is defined in terms of equation (1). The transport properties are discussed in the following section.

TRANSPORT PROPERTY CALCULATIONS

The thermal conductivity, viscosity, and surface tension are available in references

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1 and 2, with the exception of a small region near the thermodynamic critical point for thermal conductivity and a large region (573 to 647.3 K) for viscosity. For these regions, the tabulated values of references 1 and 2 represent the output of some interpolation scheme. However, no technique for predicting transport properties in these regions is given in these references.

Viscosity and Thermal Conductivity

Reference 8 uses the simple empirical technique of reference 9 to express the viscosity $\eta$ and thermal conductivity $\lambda$ of several fluids. An excess function of density $\rho$ is added to the dilute gas function of temperature $T$ such that

$$\eta = \eta_1 + \Delta \eta$$

$$\Delta \eta = \eta - \eta_1 = F(\rho)$$

$$\eta_1 = F(T) \quad \text{at} \quad P = 0.1 \text{ MN/m}^2$$

and

$$\lambda = \lambda_1 + \Delta \lambda$$

$$\Delta \lambda = \lambda - \lambda_1 = F(\rho)$$

$$\lambda_1 = F(T) \quad \text{at} \quad P = 0.1 \text{ MN/m}^2$$

We used this technique to obtain viscosity and thermal conductivity in the regions where no equation existed in references 1 and 2.

The $\Delta \eta$'s shown in figure 1 were obtained from the tabulated and computed data in references 1 and 2. These data were then extrapolated through the region where no fit is available (region 4) to predict the viscosity in that region.

Figure 1 gives a good representation for viscosity over a considerably larger range than 573 to 647.3 K, with deviations from the tabulated data up to 7 percent in some regions and perhaps 10 percent in the critical region. References 1 and 2 list uncertainties at ±4 percent in those regions where the values were not interpolated, and no uncertainties are given for the interpolated region. The analytical representations of viscosity are given in appendix B.

The $\Delta \lambda$'s used to predict thermal conductivity were also obtained from the tabulated and computed data of references 1 and 2. In this case the scatter is more acute.
over a wide range of density because these data are pressure sensitive and are not en-
tirely represented by excess thermal conductivity as a function of density, see figure 2. While the curve of figure 2 represents a wider P, T range than the region where no curve fit is available (region V) in figure 2, the \( \Delta \lambda \) curve fit is used only in region V.

Generally, deviations to 8 percent in \( \lambda \)-calculations can be found with respect to the tabulated data. References 1 and 2 give the deviations as ±4 percent in regions where curve fits exist, and no uncertainties are listed for the interpolated region. The analytic forms for thermal conductivity are given in appendix B. In region IV (fig. 2) the implicit equation for thermal conductivity from reference 2 is used. In region III an explicit expression for thermal conductivity from reference 2 is used. These forms were adopted over those of reference 1 because of their analytic nature.

The 0. 1-MN/m\(^2\) thermal conductivity and viscosity output from 700 to 1700 K was checked against the results of Svehla (ref. 10). Svehla's viscosity is 5 to 10 percent higher and his thermal conductivity is 10 to 15 percent higher than those predicted herein. Since the publishing of reference 10, Svehla has found that inclusion of a rotational relaxation effect would lower his calculated viscosity perhaps 5 percent, and lower his calculated thermal conductivity perhaps 10 to 15 percent.

Near-Critical Thermal Conductivity

The anomalous behavior of thermal conductivity in the near-critical region was measured by Le Neindre (ref. 11). Sengers (ref. 12) advanced a technique to predict the behavior of near-critical thermal conductivity data for carbon dioxide. In reference 13, Sengers' technique was modified, extended to several fluids, and compared with other methods. The technique used herein is the same as Sengers' technique as presented in reference 13, except that the proportionality constant, \( 3.05 \times 10^{-5} \) as given by Sengers in reference 12, has been increased to \( 11.6 \times 10^{-5} \).

THERMODYNAMIC AND TRANSPORT PROPERTY PLOTS

Sample plots of the properties calculated by WASP are found in figures 3 to 14.\(^3\) The triple temperature scales in these figures are to facilitate checking. Figure 3 represents density as a function of temperature for selected isobars, including the critical isobar. No irregularities were found. Figure 4(a) represents the pressure as a function of temperature for selected isochores. These isochores exhibit distinct curvature not only near the saturation boundaries but in the extended regions as well. The slopes

\(^3\)Isobars which cross the saturation boundaries are parallel to isotherms. The plotting routine simply connects increments in temperature.
of the isochores as a function of temperature are shown in figure 4(b), which reveals the nonlinear character of most of the isochores of figure 4(a). Figure 5 represents the pressure-volume (P-V) plane for selected isotherms. Local P-V regions could be mapped by using WASP for preliminary cycle analysis. Figure 6 represents enthalpy as a function of temperature for selected isobars, including the critical isobar. Figure 7 represents the temperature-entropy (T-S) diagram for selected isobars. Again, local T-S regions could be mapped by using WASP for preliminary cycle analysis.

Figure 8 represents specific heat at constant pressure and figure 9(a) represents specific heat at constant volume for selected isobars, including the critical isobar. Note the peaking effects in \( C_v \) along the critical isobar; this indicates a discontinuity in \( C_v \), as well as in \( C_p \), along the critical isobar. This behavior agrees with the most recent thinking on \( C_v \) in the critical region; namely, that \( C_v \) possesses a weak logarithmic infinity (i.e., \( C_v \propto \left| T - T_c \right|^{-0.06} \), as discussed in ref. 14). In figure 9(b), the isentropic expansion coefficient (\( \gamma = C_p/C_v \)) is given as a function of temperature for selected isobars, including the critical isobar. Note that while \( C_p \) and \( C_v \) tend toward a discontinuity, so also does the ratio. The reason is that \( C_p \) possesses a very strong "infinity" at the critical point \( C_p \propto \left| T - T_c \right|^{-\beta_1} \), where \( 1.2 < \beta_1 < 1.35 \) and \( C_v \) a rather weak "infinity." Consequently, in the critical region, \( \gamma \) diverges approximately as \( \left| T - T_c \right|^{-\beta_2} \), where \( 1.1 < \beta_2 < 1.3 \).

Figure 10 gives sonic velocity as a function of temperature for selected isobars. Sonic velocity tends toward zero, or at least a minimum, in the critical region \( C_c \), which also concurs with recent thinking because

\[
C_c \propto \frac{1}{\rho} \sqrt{\frac{T}{\rho} \frac{\partial P}{\partial T}}
\]

Since \( C_v \) diverges in a weak manner and \( (\partial P/\partial T)_{\rho} \) is nonzero and finite, \( C_c \) will approach zero in a weak manner.

Figure 11 represents a plot of viscosity as a function of temperature along selected isobars, including the critical isobar. The discontinuities of this surface at 573 and 647 K are caused by the empirical nature of the curve fit (fig. 1), as discussed previously. This discontinuity is on the average less than 4 percent, which is the same order of accuracy as presented in references 1 and 2.

Figure 12(a) represents thermal conductivity as a function of temperature along selected isobars. In this report, an attempt has been made to include the anomalous behavior of thermal conductivity in the near-critical regions based on references 12, 13, 15, and 16. The behavior of the near-critical thermal conductivity is shown in figure 12(b). In order for the user to obtain these values, he must add EXCESSK, which represents the anomalous part of the thermal conductivity, to the normally computed
value of thermal conductivity. See USER'S GUIDE TO WASP, the statement COMMON/
PROPTY/. . . . Generally, the plots of $\eta$ and $\lambda$ exhibit some irregularities where
the various predicting techniques overlap; however, for most applications the values re-
turned are within acceptable tolerance.

Figure 13 is a plot of surface tension $\sigma$ and Laplace constant as a function of tem-
perature. Metastable conditions near both the liquid and vapor are often required in a
system analysis and can be calculated by equation (1). A special subroutine is included
in appendix G which when used with WASP will give metastable properties; sample plots
are shown as figure 14.

Other Thermodynamic Functions

WASP provides sufficient PVT and derived property data for most users; however,
if other functions are required, the user may calculate these by using the partial deriva-
tives $(\partial P/\partial T)_T$ and $(\partial P/\partial T)_p$, along with the other results from WASP. Appendix H is
provided to give the user a handy reference to the so-called Bridgeman Tables which
list most of the interrelations between thermodynamic variables. (See pp. 36 and 64.)

Comparison Plots

Of utmost importance is how well equation (1), as used in WASP, agrees with the
International Skeleton Tables for steam and water (refs. 1 and 2). Figures 15 to 17 were
obtained by running all the data points listed in table 1.2 of reference 1 (see also table 4b
of ref. 2) on each of the three input options $(T, P)$, $(\rho, T)$, and $(\rho, P)$ in WASP. Each of
the figures is discussed, but the careful reader should note that discrepancies exist in
the specific volumes presented in these two references. The authors noted four obvious
errors in reference 2 by comparing references 1 (table 1.2) and 2 (table 4b). Refer-
ence 1 was assumed to be correct. Other discrepancies occur in reference 2, for in-
stance in the specific heat $C_p$. No attempt was made to track all these errors, and the
reader should use reference 2 cautiously.

Figure 15 represents the percent relative error in density, \[\frac{(\rho_{\text{table}} - \rho_{\text{calc}})}{\rho_{\text{table}}} \times 100,\] as a function of density. With the exception of three points, all the
values are within $-0.25$ percent and $-0.50$ percent, and generally have an error of less
than 1 part in 3000. The solution for density is iterative, and perhaps the error could be
reduced somewhat by a tightening of the convergence criteria. This is not recommended
for two reasons: (1) It will require a great increase in computer time, and (2) errors in
these printed tables have been noted. The tolerance should be quite satisfactory to all
but the most critical user.
Figure 16 represents the percent relative error in pressure, \( \frac{(P_{\text{table}} - P_{\text{calc}})}{P_{\text{table}}} \times 100 \), as a function of pressure. In all cases the calculated pressures are within +3.0 percent and -2.0 percent of the tabulated value; most points lie within +0.25 percent of the tabulated value. The prediction of pressure at high density (low temperatures) using a fundamental equation or a state equation is quite difficult. These pressure errors are all within accepted tolerances.

Figure 17 represents the percent relative error in temperature, \( \frac{(T_{\text{table}} - T_{\text{calc}})}{T_{\text{table}}} \times 100 \), as a function of temperature. With the exception of about a dozen points, the predicted temperatures are within +0.25 percent and -0.4 percent and generally lie within ±0.1 percent.

Usually, temperature and density are predictable because of the manner in which the data were acquired; however, pressure is always difficult to calculate. With these basic guidelines in mind and figures 15 to 17, it can be said that the equation gives a faithful representation of the International Skeleton Tables (refs. 1 and 2).

**USER'S GUIDE TO WASP**

The user with limited programming experience should have no difficulty in following the operating instructions for WASP. After gaining a little experience with WASP, the only references needed are table I (the operations sheet) and table II (the units specification).

**How WASP Handles Input/Output**

WASP is a group of subroutines designed to be used as a subprogram with the user's program. Standard communication between the user's program and WASP is achieved by the following two FORTRAN statements, which contain the symbols representing the input/output parameters and options:

```fortran
COMMON/PROPTY/KU, DL, DV, HL, HV, etc.
CALL WASP (KS, KP, T, P, D, H, KR)
```

See table I and appendix A.

Three requirements must be fulfilled for a successful call to WASP:

1. The cards for COMMON/PROPTY/KU, DL, DV, etc., must be included in the user's main program or the subroutine that calls WASP. The WASP subprogram deck must be correctly loaded with the user's program as shown in table III. The variables MU, MUL, MUV, K, KL, and KV must be declared REAL. (K cannot be used as an
(2) The units system for input/output must be correctly specified. $KU$ is an input control specified in the COMMON/PROPTY/KU, DL, DV, etc., which must be set such that $1 \leq KU \leq 5$. $KU$ identifies the units system for input/output, and $KU$ is never altered by WASP. Therefore, unless the user switches from one system to another, he need set his value for $KU$ only once, before any calls to subroutine WASP.

There are three specified units options described in table II. The option $KU=1$ is the internal program units system. The other two options are commonly used in engineering calculations. If the user does not wish to use one of these options, he can specify any desired units system for $KU=4$ and $KU=5$, provided the conversion factors for this system are stored by the user as directed in table II.

(3) The controls $KR$, $KS$, and $KP$, which tell WASP what variables are to be used as input and what properties are requested for output, must be correctly initialized in the call statement for subroutine WASP. The corresponding input variables in the call statement and COMMON/PROPTY/... must also be correctly initialized.

$KS$ and $KR$ are controls that determine which of the variables $T$, $P$, $D$, $H$, or $S$ or combinations thereof are needed as thermodynamic input. $KP$ is an input control which specifies which properties are sought as output.

$KR$ is also an output variable since it gives the correct region number for the variables in a specific call to WASP, as shown in the sketch in table I. Depending on the input for $KS$ and $KP$, the other possible output variables are $T$, $P$, $D$, $H$, and all of COMMON/PROPTY/ except the control $KU$.

As mentioned above, $KR$ is both input and output and must be reset before each call to WASP. The input options are

(a) $KR=0$ when user wishes WASP to determine a value for $KR$
(b) $KR=1$ when user wishes saturation conditions$^4$

The output for $KR$ will be

(a) $KR=1$ for saturation
(b) $KR=2$ for liquid
(c) $KR=3$ for vapor

$KS$ specifies which variables are to be used as input for a call to subroutine WASP.

(In the remaining discussion on WASP input/output, the input variables are assumed to be in user's units specified by $KU$. Output is always returned in the $KU$ system of units.)

$^4$Saturation or coexistence conditions exist on the PVT surface when pressure is a function of only temperature and the liquid and vapor states both exist at that pressure. Thus when $KR=1$, two outputs for each property are available in COMMON/PROPTY/ and only one independent variable is required for some input options, as shown in the $KS$-$KR$ input/output chart.
The following table shows the input and output for all KS, KR combinations:

<table>
<thead>
<tr>
<th>Thermodynamic region specification, KR</th>
<th>State relation specification, KS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td><strong>Input</strong></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>T and P</td>
</tr>
<tr>
<td>1</td>
<td>T or P&lt;sup&gt;a&lt;/sup&gt;, T and D, P and D, P and H, P and S</td>
</tr>
<tr>
<td><strong>Output</strong></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>T or P&lt;sup&gt;a&lt;/sup&gt;, T and D, P and D, P and H, P and S</td>
</tr>
<tr>
<td>2</td>
<td>D</td>
</tr>
<tr>
<td>3</td>
<td>D</td>
</tr>
</tbody>
</table>

<sup>a</sup> If T is the desired input, set P = 0.0 prior to the call and vice versa. Then WASP will return the correct saturation value for the 0.0 input. If both T and P have an input value ≠ 0.0, WASP uses T but will not alter P input.

**KP** is an input control that specifies which derived and transport properties are requested by the user. It is the sum of the individual KP options and is described in Table I. This binary sum allows WASP to uniquely identify any combination of requests. The following table shows the output locations for the specific KR and KP combinations:

<table>
<thead>
<tr>
<th>Value added to KP input</th>
<th>Output for KR=2 or 3</th>
<th>Output for KR=1</th>
<th>Name of calculated property</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Liquid</td>
<td>Vapor</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>1</td>
<td>H</td>
<td>HL</td>
<td>HV</td>
</tr>
<tr>
<td>2</td>
<td>S</td>
<td>SL</td>
<td>SV</td>
</tr>
<tr>
<td>4</td>
<td>CP</td>
<td>CPL</td>
<td>CPV</td>
</tr>
<tr>
<td>4</td>
<td>CV</td>
<td>CVL</td>
<td>CVV</td>
</tr>
<tr>
<td>4</td>
<td>GAMMA</td>
<td>GAMMAL</td>
<td>GAMMAV</td>
</tr>
<tr>
<td>8</td>
<td>C</td>
<td>CL</td>
<td>CVP</td>
</tr>
<tr>
<td>16</td>
<td>MU</td>
<td>MUL</td>
<td>MUV</td>
</tr>
<tr>
<td>32</td>
<td>K</td>
<td>KL</td>
<td>KV</td>
</tr>
<tr>
<td>32</td>
<td>SIGMA</td>
<td>SIGMA</td>
<td>---</td>
</tr>
<tr>
<td>32</td>
<td>ALC</td>
<td>ALC</td>
<td>---</td>
</tr>
</tbody>
</table>
Troubleshooting for User Errors

After experience with WASP, we have found that several common errors are easily detected and corrected.

(1) Failure to set \( 1 \leq KU \leq 5 \) will cause a "division by 0.0" and/or no valid answers. Set \( KU \) to its proper value.

(2) Failure to set \( 1 \leq KS \leq 5 \) will most likely cause a halt to the program because of an execution error. The branching on \( KS \) in subroutine WASP is a computed "GO TO." Simply set \( KS \) to its proper value.

(3) Failure to set \( KP \) will return enthalpy if \( KP \) is odd and no derived properties if \( KP \) is even.

(4) If a wrong value is entered for \( KR \), it is treated as \( KR=0 \). If a user enters \( KR=1 \) when he does not want saturation properties, he will get them anyway for \( T < T_c \) and otherwise will get a wrong answer.

(5) If any \( T, P, D, H, \) or \( S \) is entered incorrectly, that value will be used and the answer will be wrong.

(6) If the COMMON/PROPTY/ is duplicated incorrectly, there are a variety of possible errors, almost all serious.

Other small problems may be encountered if WASP is modified for different compilers or computers. The FORTRAN IV coding in WASP is machine independent except for a few Hollerith format statements which can be easily changed. The reader who needs more detailed information should read the appendixes.

Additional Information

The approximate core storage for the complete WASP program is \((14650)_8 = (6568)_{10}\) locations.

The time estimates were obtained by running an average of 100 calls over the entire PVT range for each option indicated. The shortest call was for pressure, \( KS=2 \), at an average of 4 milliseconds per call for \( T > T_c \) and 17 milliseconds for \( T < T_c \). The call for density, \( KS = 1 \), varied from 17 to 40 milliseconds for all regions, with the greatest time being consumed in the near-critical region. The call for temperature, \( KS=3 \), varied from 11 to 70 milliseconds per call, with the least time used when \( P > P_c \) and the most time used in the near-critical region. The call for density and all the derived properties, \( KS=1 \) and \( KP=63 \), varied from 38 to 120 milliseconds per call depending on the density call and the regions for the transport properties.

The \( P, H \) and \( P, S \) calls, \( KS=4 \) and \( KS=5 \), each required from 300 to 800 milliseconds per call, with the greatest time in the near-critical region. These results are summarized as follows:
Problems Previously Encountered When Converting to Non-IBM Machines

or Different FORTRAN IV - FORTRAN V Compilers

The problems encountered in converting to different equipment are as follows:

(1) IBM 360 users should run in double precision by inserting implicit REAL*8 (A-H, O-Z) and REAL*8 MU, MUL, MUV, K, KL, KV in subroutine WASP and implicit REAL*8 (A-H, O-Z) in all other subroutines. Change COMMON/PROPTY/KU, KZ, DL, DV, etc., for proper alignment.

(2) Data statements are found in subroutines BLOCK DATA, THERM, VISC, and SURF. Many compilers differ in formatting data statements.

(3) The multiple-entry routine (CHECK, TCHECK, PCHECK, DCHECK) has an entry point, DCHECK, whose input vector (KU, D) does not correspond in kind and number with the other entry points (KU, KR, T) or (KU, KR, P). To our knowledge this has caused a problem on only one compiler, a FORTRAN IV for a CDC 3800. It was easily remedied by an equivalence statement.

The authors adapted the code to fit the following compilers and machines: UNIVAC 1108, CDC 3600, CDC 6600, IBM 360/67TSS, and IBM 7094-7044 DCS.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 26, 1973,
502-04.
# APPENDIX A

## SYMBOLS

<table>
<thead>
<tr>
<th>Mathematical symbol</th>
<th>FORTRAN symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{ij}$</td>
<td>A(I, J)</td>
<td>coefficients of terms in $Q$-function (see table IV)</td>
</tr>
<tr>
<td>ALC</td>
<td></td>
<td>Laplace constant</td>
</tr>
<tr>
<td>$c$</td>
<td>C</td>
<td>sonic velocity, cm/sec</td>
</tr>
<tr>
<td>CL</td>
<td></td>
<td>sonic velocity of saturated liquid, cm/sec</td>
</tr>
<tr>
<td>CVP</td>
<td></td>
<td>sonic velocity of saturated gas, cm/sec</td>
</tr>
<tr>
<td>$C_1$</td>
<td>SIC1</td>
<td>coefficients of terms in $\psi_0$ function (see table IV)</td>
</tr>
<tr>
<td>$C_5$</td>
<td>SIC5</td>
<td>coefficients of terms in $\psi_0$ function (see table IV)</td>
</tr>
<tr>
<td>$C_p$</td>
<td>CP</td>
<td>specific heat at constant pressure, J/(g)(K)</td>
</tr>
<tr>
<td>CPL</td>
<td></td>
<td>specific heat $C_p$ of saturated liquid, J/(g)(K)</td>
</tr>
<tr>
<td>CPV</td>
<td></td>
<td>specific heat $C_p$ of saturated vapor, J/(g)(K)</td>
</tr>
<tr>
<td>$C_v$</td>
<td>CV</td>
<td>specific heat at constant volume, J/(g)(K)</td>
</tr>
<tr>
<td>CVL</td>
<td></td>
<td>specific heat $C_v$ of saturated liquid, J/(g)(K)</td>
</tr>
<tr>
<td>CVV</td>
<td></td>
<td>specific heat $C_v$ of saturated vapor, J/(g)(K)</td>
</tr>
<tr>
<td>$D_1$</td>
<td>CPS1</td>
<td>coefficients for vapor pressure curve (see table IV)</td>
</tr>
<tr>
<td>$D_7$</td>
<td>CPS7</td>
<td>coefficients for vapor pressure curve (see table IV)</td>
</tr>
<tr>
<td>E</td>
<td>E</td>
<td>$E = 4.8$</td>
</tr>
<tr>
<td>H</td>
<td>H</td>
<td>enthalpy, J/g</td>
</tr>
<tr>
<td>HL</td>
<td></td>
<td>enthalpy of saturated liquid, J/g</td>
</tr>
</tbody>
</table>

5Symbols used in each individual subroutine are identified in that subroutine (see appendix C).
HV \quad \text{enthalpy of saturated vapor, J/g}

KP \quad \text{thermodynamic and transport properties specification}

KR \quad \text{thermodynamic region specification}

KS \quad \text{state relation specification}

KU \quad \text{units specification}

P \quad P \quad \text{pressure, MN/m}^2

Q \quad QCALC \quad \text{data-fitting function}

R \quad R \quad \text{specific gas constant for water, 0.46151 J/(g)(K)}

S \quad S \quad \text{entropy, J/(g)(K)}

SL \quad \text{entropy of saturated liquid, J/(g)(K)}

SV \quad \text{entropy of saturated vapor, J/(g)(K)}

T \quad T \quad \text{temperature, K}

u \quad \text{internal energy, J/g}

\gamma \quad \text{GAMMA} \quad \text{ratio of specific heats, } \frac{C_p}{C_v}

\gamma_{\text{GAMMAL}} \quad \text{ratio of specific heats for saturated liquid}

\gamma_{\text{GAMMAV}} \quad \text{ratio of specific heats for saturated vapor}

\eta \quad \text{MU} \quad \text{dynamic viscosity, g/(cm)(sec)}

\eta_{\text{MUL}} \quad \text{dynamic viscosity of saturated liquid, g/(cm)(sec)}

\eta_{\text{MUV}} \quad \text{dynamic viscosity of saturated vapor, g/(cm)(sec)}

\lambda \quad \text{K} \quad \text{thermal conductivity, W/(cm)(K)}

\lambda_{\text{KL}} \quad \text{thermal conductivity of saturated liquid, W/(cm)(K)}

\lambda_{\text{KV}} \quad \text{thermal conductivity of saturated vapor, W/(cm)(K)}

\rho \quad \text{D} \quad \text{density, g/cm}^3

\rho_{\text{L}} \quad \text{DL} \quad \text{density of saturated liquid, g/cm}^3

\rho_{\text{V}} \quad \text{DV} \quad \text{density of saturated vapor, g/cm}^3

\rho_a \quad \text{RHOA} \quad \text{constant used in Q-function, } \rho_a = 0.634

\rho_b \quad \text{RHOB} \quad \text{constant used in Q-function, } \rho_b = 1.0

\sigma \quad \text{SIGMA} \quad \text{surface tension, dyne/cm}

\tau = \frac{1000}{T} \quad \text{TAU} \quad \text{temperature parameter, K}^{-1}
\( \tau_a \)  \( \text{TAUA} \)
\( \tau_c \)  \( \text{TAUC} \)
\( \psi \)  \( \text{PSI} \)
\( \psi_0 \)  \( \text{PSIO} \)
\( \frac{d\psi_0}{dT} \)  \( \text{PSIT} \)
\( \left( \frac{\partial Q}{\partial \tau} \right)_\rho \)  \( \text{QTD} \)
\( \left( \frac{\partial Q}{\partial \rho} \right)_\tau \)  \( \text{QDT} \)
\( \left( \frac{\partial^2 Q}{\partial \tau^2} \right)_\rho \)  \( \text{Q2T2D} \)
\( \left( \frac{\partial^2 Q}{\partial \rho^2} \right)_\tau \)  \( \text{Q2D2T} \)
\( \frac{\partial^2 Q}{\partial \tau \partial \rho} \)  \( \text{Q2DT} \)

constant used in Q-function, \( \tau_a = 2.5 \)

1000 divided by critical temperature expressed in kelvin

Helmholtz free energy, J/g

reference function, J/g

partial derivatives used in evaluating \( \psi \) and its derivatives
APPENDIX B

PROPERTY EQUATIONS OF WASP

The equations used in WASP were those taken from Keyes, Keenan, Hill, and Moore (ref. 3), Schmidt (ref. 2) and the ASME Steam Tables (ref. 1) and those developed by the authors.

FUNDAMENTAL EQUATION

The basic equation of WASP expresses the Helmholtz free energy in terms of $\rho$ and $T$,

$$\psi = \psi(\rho, T)$$  \hspace{1cm} (B1)

whereas the equation of state is usually expressed as

$$P = P(\rho, T)$$  \hspace{1cm} (B2)

Equation (B1) is complete inasmuch as the required thermodynamic functions are derivatives of $\psi$ and undetermined constants and/or functions are not required. For example, specific heat at "zero" pressure $C_{p0}$, which is a function of temperature, is not required in the $\psi$-form; however, in the $P$-form (eq. (B2)), $C_{p0}$ is required to obtain entropy, enthalpy, and specific heats.

When equation (B1) is expanded, $\psi$ becomes

$$\psi = \psi_0(T) + RT[\ln \rho + \rho Q(\rho, \tau)]$$  \hspace{1cm} (B3)

where

$$Q = \sum_{i=1}^{8} A_{1i}(\rho - \rho_a)^{i-1} + e^{-E\rho(A_{9i} + A_{10i}\rho)}$$

$$+ (\tau - \tau_a)\left\{ \sum_{j=2}^{7} (\tau - \tau_a)^{j-2} \left[ \sum_{i=1}^{8} A_{ij}(\rho - \rho_b)^{i-1} + e^{-E\rho(A_{9j} + A_{10j}\rho)} \right] \right\}$$  \hspace{1cm} (B4)
\[ \psi_0(T) = C_1 + C_2 T + C_3 T^2 + (C_4 + C_5 T) \ln T \] (B5)

\[ \tau = \frac{1000}{T} \] (B6)

\[ \rho_a = 0.634 \text{ g/cm}^3 \]
\[ \rho_b = 1.0 \text{ g/cm}^3 \]
\[ \tau_a = 2.5 \text{ K}^{-1} \]
\[ \tau_c = 1.544912 \text{ K}^{-1} \]
\[ E = 4.8 \text{ cm}^3/\text{g} \]
\[ R = 0.46151 \text{ J/(g)(K)} \] (B7)

and the constants \( C_1, \ldots, C_5 \) and \( A_{ij} \) are given in table IV.

**DERIVATIVES OF Q**

The derivatives of \( Q \) are required to evaluate any of the thermodynamic properties:

\[ \left( \frac{\partial Q}{\partial \tau} \right)_\rho = \left\{ \sum_{j=2}^{7} (\tau - \tau_a)^{j-2} \left[ \sum_{i=1}^{8} A_{ij}(\rho - \rho_b)^{i-1} + e^{-E\rho}(A_{9j} + A_{10j}\rho) \right] \right\} \]

\[ + (\tau - \tau_c) \left\{ \sum_{j=3}^{7} (j - 2)(\tau - \tau_a)^{j-3} \left[ \sum_{i=1}^{8} A_{ij}(\rho - \rho_b)^{i-1} + e^{-E\rho}(A_{9j} + A_{10j}\rho) \right] \right\} \] (B8)

\[ \left( \frac{\partial Q}{\partial \rho} \right)_\tau = \sum_{i=2}^{8} (i-1)A_{i1}(\rho - \rho_a)^{i-2} + e^{-E\rho} \left[ E(A_{9,1} + A_{10,1}) + A_{10,1} \right] \]

\[ + (\tau - \tau_c) \left\{ \sum_{j=2}^{7} (\tau - \tau_a)^{j-2} \left[ \sum_{i=2}^{8} (i-1)A_{ij}(\rho - \rho_b)^{i-2} + e^{-E\rho} \left[ - (A_{9j} + A_{10j}\rho)E + A_{10j} \right] \right] \right\} \] (B9)
\[
\frac{\partial^2 Q}{\partial p \partial \tau} = \sum_{j=2}^{7} (\tau - \tau_a)^{j-2} \left[ \sum_{i=2}^{8} (1 - 1)A_{ij}(\rho - \rho_b)^{i-2} + e^{-EP(-E_{A_9j} - E_{A_{10}j} + A_{10}j)} \right] \\
+ (\tau - \tau_c) \left\{ \sum_{j=3}^{7} (j - 2)(\tau - \tau_a)^{j-3} \left[ \sum_{i=2}^{8} (1 - 1)A_{ij}(\rho - \rho_b)^{i-2} + e^{-EP(-E_{A_9j} - E_{A_{10}j} + A_{10}j)} \right] \right\} \\
(B10)
\]

\[
\frac{\partial^2 Q}{\partial \rho^2}_{\tau} = \sum_{i=3}^{8} A_{i1}(i - 1)(i - 2)(\rho - \rho_a)^{i-3} + e^{-EP\left\{ -E_{A_9,1} + A_{10,1}(2 - E_{\rho}) \right\}} \\
+ (\tau - \tau_c) \left\{ \sum_{j=2}^{7} (\tau - \tau_a)^{j-2} \left[ \sum_{i=3}^{8} A_{ij}(i - 1)(i - 2)(\rho - \rho_b)^{i-3} + e^{-EP\left\{ -E_{A_9j} + A_{10j}(2 - E_{\rho}) \right\}} \right] \right\} \\
(B11)
\]

\[
\frac{\partial^2 Q}{\partial \tau^2}_{\rho} = 2 \left\{ \sum_{j=3}^{7} (j - 2)(\tau - \tau_a)^{j-3} \left[ \sum_{i=1}^{8} A_{ij}(\rho - \rho_b)^{i-1} + e^{-EP(A_{9j} + A_{10j}\rho)} \right] \right\} \\
+ (\tau - \tau_c) \left\{ \sum_{j=4}^{7} (j - 2)(j - 3)(\tau - \tau_a)^{j-4} \left[ \sum_{i=1}^{8} A_{ij}(\rho - \rho_b)^{i-1} + e^{-EP(A_{9j} + A_{10j}\rho)} \right] \right\} \\
(B12)
\]

**THERMODYNAMIC PROPERTIES**

The derivatives of \( \psi \) give all the functions necessary to obtain the thermodynamic properties.

**Pressure and Its Derivatives**

\[
P = \rho^2 \frac{\partial^2 \psi}{\partial \rho^2} = \rho R \frac{1000}{\tau} \left[ 1 + \rho Q + \rho^2 \frac{\partial^2 Q}{\partial \rho^2} \right] \\
(B13)
\]
Enthalpy and Its Derivatives

\[ H = u + \frac{P}{\rho} \]  
\[ \frac{\partial P}{\partial \rho} = \frac{1000 R}{\tau} \left[ 1 + 2\rho Q + 4\rho^2 \left( \frac{\partial Q}{\partial \rho} \right) + \rho^3 \left( \frac{\partial^2 Q}{\partial \rho^2} \right) \right] \]  
\[ \frac{\partial P}{\partial \tau} = -1000 \rho R \left[ 1 + 2\rho Q + \rho^2 \left( \frac{\partial Q}{\partial \rho} \right) \right] - R\rho^2 \left( \rho \left( \frac{\partial Q}{\partial \tau} \right) + \left( \frac{\partial Q}{\partial \rho} \right) \right) \]  
\[ \frac{\partial P}{\partial T} = -\frac{\partial P}{\partial \rho} \frac{T^2}{1000} \]  

where the first term of equation (B19) is the internal energy \( u \).
\[
\frac{\partial H}{\partial T} = -T \frac{d^2 \psi_0}{dT^2} + R \left[ 1 + \rho Q + \rho^2 \frac{\partial Q}{\partial \rho} - \tau \rho \frac{\partial Q}{\partial T} - \rho \frac{\partial^2 Q}{\partial T \partial \rho} - \rho \frac{\partial^2 Q}{\partial T^2} \right] \tag{B21}
\]

\[
\frac{\partial H}{\partial \rho} = \frac{1000 \, R}{\tau} \left\{ Q + \tau \left[ \rho \frac{\partial Q}{\partial \rho} + \rho \frac{\partial^2 Q}{\partial \rho \partial T} \right] + \rho \left[ 3 \frac{\partial Q}{\partial \rho} + \rho \frac{\partial^2 Q}{\partial \rho^2} \right] \right\} \tag{B22}
\]

**Entropy**

\[
S = -\frac{\partial \psi}{\partial T} \tag{B23}
\]

\[
S = -R \left\{ \ln \rho + \rho \left[ Q - \tau \frac{\partial Q}{\partial T} \right] - \frac{d \psi_0}{dT} \right\} \tag{B24}
\]

**Specific Heats**

**Constant volume:**

\[
C_v = \frac{\partial u}{\partial T} \tag{B25}
\]

\[
C_v = - \left[ R \rho^2 \frac{\partial^2 Q}{\partial T^2} + T \frac{d^2 \psi_0}{dT^2} \right] \tag{B26}
\]

**Constant pressure:**

\[
C_p = \frac{\partial H}{\partial T} - \rho \frac{\partial H}{\partial \rho} \left[ \frac{\partial \rho}{\partial T} \frac{\partial \rho}{\partial \rho} \right] \tag{B27}
\]
"Isentropic" expansion coefficient:

\[ \gamma = \frac{C_p}{C_v} \]  

\hspace{10cm} \text{(B28)}

\[
\text{Sonic Velocity}
\]

\[ C_s^2 = \left( \frac{\partial P}{\partial \rho} \right)_S \]  

\hspace{10cm} \text{(B29)}

\[ C_s^2 = \gamma \left( \frac{\partial P}{\partial \rho} \right)_T \]  

\hspace{10cm} \text{(B30)}

\[
\text{Vapor Pressure Curve}
\]

\[ \log_{10} P = (1 + D_1) + \sum_{j=3}^{7} D_j(T - 273.15)^j + \frac{D_2}{T - 273.15} \]  

\hspace{10cm} \text{(B31)}

where the original data are in bars and °C whereas pressure and temperature in the program are in MN/m² and K, hence the forms \((1 + D_1)\) and \((T - 273.15)\).

\[
\text{TRANSPORT PROPERTIES}
\]

The transport property equations are not as concisely defined as the fundamental equation. The transport maps for viscosity and thermal conductivity are broken into several regions, as shown in sketches a and b, respectively, and individual curve fits are presented for each. Also, several regions are void of description as they exist in references 1 and 2.
Viscosity

Atmospheric pressure. - For $P = 0.1 \text{ MN/m}^2$ and $373.15 \text{ K} < T < 973.15 \text{ K},$

$$\eta_1 = \left[ b_1 \left( \frac{T}{T_c} \right) - b_2 \right] + b_3 \times 10^{-6} \quad \text{(B32)}$$

Region 1. - For $P_{\text{sat}} < P < 80 \text{ MN/m}^2$ and $273.15 \text{ K} < T < 573.15 \text{ K},$

$$\eta = 10^{-6} a_1 \left[ 1 + \left( \frac{\rho}{\rho_c} - \frac{P_{\text{sat}}}{P_c} \right) \times a_4 \left( \frac{T}{T_c} - a_5 \right) \right] \times 10^{\left[ \frac{a_2}{(T/T_c) - a_3} \right]} \quad \text{(B33)}$$

Region 2. - For $0.1 \text{ MN/m}^2 < P < P_{\text{sat}}$ and $373.15 \text{ K} < T < 573.15 \text{ K},$

$$\eta = \left\{ \eta_1 \times 10^6 - 10 \frac{\rho}{\rho_c} \left[ c_1 - c_2 \left( \frac{T}{T_c} - c_3 \right) \right] \right\} \times 10^{-6} \quad \text{(B34)}$$

Region 3. - For $0.1 \text{ MN/m}^2 < P < 80 \text{ MN/m}^2$ and $648.15 \text{ K} < T < 1073.15 \text{ K},$

$$\eta = \left[ \eta_1 \times 10^6 + d_3 \left( \frac{\rho}{\rho_c} \right)^3 + d_2 \left( \frac{\rho}{\rho_c} \right)^2 + d_1 \left( \frac{\rho}{\rho_c} \right) \right] \times 10^{-6} \quad \text{(B35)}$$
Region 4. - Tabulated values of viscosity in region 4, as well as computed values of viscosity at equivalent densities, were plotted as per figure 1. The resulting curve gives an accurate representation of these data, with the exception of those values along the saturation locus in the near-critical region. As can be seen, deviations of up to 7 percent, and 10 percent at the critical point, are common.

\[
\begin{align*}
  k = 1 & \quad \text{for } \rho / \rho_c \leq 4/3 \\
  k = 2 & \quad \text{for } \rho / \rho_c > 4/3
\end{align*}
\]

(B36)

\[
\eta = \eta_1 + \frac{10^Y}{0.0192}
\]

(B37)

where

\[
Y = C_{5k}X^4 + C_{4k}X^3 + C_{3k}X^2 + C_{2k}X + C_{1k}
\]

(B38)

\[
X = \log_{10}\left(\frac{\rho}{\rho_c}\right)
\]

(B39)

The following coefficients are used in the viscosity equations:

\[
\begin{align*}
a_1 &= 241.4 & c_1 &= 586.1198738 \\
a_2 &= 0.3828209486 & c_2 &= 1204.753943 \\
a_3 &= 0.2162830218 & c_3 &= 0.4219836243 \\
a_4 &= 0.1498693949 & d_1 &= 111.3564669 \\
a_5 &= 0.4711880117 & d_2 &= 67.32080129 \\
b_1 &= 263.4511 & d_3 &= 3.205147019 \\
b_2 &= 0.4219836243 \\
b_3 &= 80.4
\end{align*}
\]
For $k = 2,$

\begin{align*}
C_{1k} &= -6.4556581 \\
C_{2k} &= 1.3949436 \\
C_{3k} &= 0.30259083 \\
C_{4k} &= 0.10960682 \\
C_{5k} &= 0.015230031
\end{align*}

\begin{align*}
C_{1k} &= -6.4608381 \\
C_{2k} &= 1.6163321 \\
C_{3k} &= 0.07097705 \\
C_{4k} &= -13.938 \\
C_{5k} &= 30.119832
\end{align*}

**Thermal Conductivity**

*Atmospheric pressure.* - For $P = 0.1 \text{ MN/m}^2$ and $373.15 \text{ K} < T < 973.15 \text{ K},$

\[ \lambda_1 = (17.6 + 0.0587 t + 1.04 \times 10^{-4} t^2 - 4.51 \times 10^{-8} t^3) \times 10^{-5} \]  

(B40)

where

\[ t = T - 273.15 \]  

(B41)

*Region I.* - For $P_{\text{sat}} < P < 50.0 \text{ MN/m}^2$ and $273.15 \text{ K} < T < 623.15 \text{ K},$

\[ \lambda = \left\{ S_1 + \left( \frac{P - P_{\text{sat}}}{P_c} \right) S_2 + \left( \frac{P - P_{\text{sat}}}{P_c} \right)^2 S_3 \right\} \times 10^{-2} \]  

(B42)
where

\[ S_1 = \sum_{i=0}^{4} a_i \left( \frac{T}{T_c} \right)^i \]  \hspace{1cm} (B43)

\[ S_2 = \sum_{i=0}^{3} b_i \left( \frac{T}{T_c} \right)^i \]  \hspace{1cm} (B44)

\[ S_3 = \sum_{i=0}^{3} c_i \left( \frac{T}{T_c} \right)^i \]  \hspace{1cm} (B45)

**Region II.** - For the following ranges of pressure (in MN/m²) and temperature (in K):

- \(0.1 < P \leq 17.5\) and \(T_{sat} < T < 973.15\)
- \(17.5 < P \leq 22.5\) and \(673.15 < T < 973.15\)
- \(22.5 < P \leq 27.5\) and \(698.15 < T < 973.15\)
- \(27.5 < P \leq 35.0\) and \(723.15 < T < 973.15\)
- \(35.0 < P \leq 45.0\) and \(773.15 < T < 973.15\)
- \(45.0 < P \leq 50.0\) and \(823.15 < T < 973.15\)

thermal conductivity is

\[
\lambda = \left[ \lambda_1 + (103.51 + 0.4198 t - 2.771 \times 10^{-5} t^2) \rho + \frac{2.1482 \times 10^{14}}{t^{4.2}} \rho^2 \right] \times 10^{-5} \]  \hspace{1cm} (B46)

where

\[ t = T - 273.15 \]  \hspace{1cm} (B47)
Region III. - If the \((P, T)\) is not in region II (see eq. (B54)) but \(P < 50 \text{ MN/m}^2\) and \(373.15 \text{ K} < T < 973.15 \text{ K}\), then the following should be used:

\[
\lambda = \frac{A \left(\frac{T}{T_c}\right)^{1.445}}{1 - B d_{31} \left(\frac{T}{T_c}\right)^{-7}} + \frac{d_{32} \left(\frac{P}{P_c}\right)^4 \exp\left[\frac{-9 d_{33} \left(\frac{T}{T_c}\right) - 1}{1 + d_{34} \left(\frac{P}{P_c}\right)^{-12}}\right]}{1 + d_{34} \left(\frac{P}{P_c}\right)^{-12}} \times \left\{d_{35} - d_{36} \left(\frac{P}{P_c}\right) \exp\left[-d_{33} \left(\frac{T}{T_c}\right) - 1\right]\right\}
\]

(B48)

\[A = a_{31} \left(\frac{P}{P_c}\right) + a_{32}\]  

(B49)

\[B = \frac{b_{31} \left(\frac{P}{P_c}\right)^{1.63}}{1 + b_{32} \left(\frac{P}{P_c}\right)^{3.26}}\]  

(B50)

\[C = \frac{c_{31} \left(\frac{P}{P_c}\right)^{1.5} + c_{32}}{B} - c_{33}\]  

(B51)

Region IV. - If the \((P, T)\) is not in region III (see eq. (B54)) but \(P < 50 \text{ MN/m}^2\) and \(T > 623.15 \text{ K}\), then the following should be used:

\[
\left(\frac{T}{T_c}\right) = \sum_{i=0}^{8} a_{4i} k^i + \left(\frac{P}{P_c} - c_{40}\right) \sum_{i=0}^{8} b_{4i} k^i
\]

(B52)

where

\[k = 100 \lambda\]  

(B53)

The solution for \(\lambda\) is iterative. And
Region V. - In region V, tabulated values of thermal conductivity as well as computed values of thermal conductivity at equivalent densities were plotted as per figure 2. The resulting curve gives a good representation of the tabulated values, except along the saturation locus. However, deviations up to 8 percent, and 10 percent near critical, can be expected as listed in the table. These tabulated data and this curve fit do not include the anomalous behavior of thermal conductivity in the near-critical region.

\[
\frac{P}{P_c} = \sum_{i=0}^{2} e_1 \left( \frac{T}{T_c} \right)^i
\]  

(B54)

is the boundary of region III-IV.

\[
k = 1 \quad \text{for } \frac{\rho}{\rho_c} \leq 2.5
\]  

(B55)

\[
k = 2 \quad \text{for } \frac{\rho}{\rho_c} > 2.5
\]  

(B56)

\[
\lambda = \lambda_1 + 10^Y
\]  

(B57)

where

\[
Y = C_{5k}X^4 + C_{4k}X^3 + C_{3k}X^2 + C_{2k}X + C_{1k}
\]  

(B58)

and

\[
X = \log_{10} \left( \frac{\rho}{\rho_c} \right)
\]  

(B59)
The constants used in equation (B58) are as follows:

For $k = 1$,

- $C_{1k} = -0.5786154$
- $C_{2k} = 1.4574646404$
- $C_{3k} = 0.17006978$
- $C_{4k} = 0.1334805$
- $C_{5k} = 0.032783991$

For $k = 2$,

- $C_{1k} = -0.70859254$
- $C_{2k} = 0.94131399$
- $C_{3k} = 0.06426434$
- $C_{4k} = 1.85363188$
- $C_{5k} = 1.98065901$

The following coefficients are used in the equations for thermal conductivity:

- $a_0 = -0.92247$
- $a_1 = 6.728934102$
- $a_2 = -10.11230521$
- $a_3 = 6.996953832$
- $a_4 = -2.31606251$
- $a_{31} = 0.01012472978$
- $a_{32} = 0.05141900883$
- $a_{40} = 1.365350409$
- $a_{41} = -4.802941449$
- $b_0 = -0.20954276$
- $b_1 = 1.320227345$
- $b_2 = -2.485904388$
- $b_3 = 1.517081933$
- $b_{31} = 6.637426916 \times 10^5$
- $b_{32} = 1.388806409$
- $b_{40} = 1.514476538$
- $b_{41} = -19.58487269$
- $b_{42} = 113.6782784$
\[
\begin{align*}
a_{42} &= 23.60292291 \\
a_{43} &= -51.44066584 \\
a_{44} &= 38.86072609 \\
a_{45} &= 33.47617334 \\
a_{46} &= -101.0369288 \\
a_{47} &= 101.2258396 \\
a_{48} &= -45.69066893 \\
b_{43} &= -327.0035653 \\
b_{44} &= 397.3645617 \\
b_{45} &= 96.82365169 \\
b_{46} &= -703.0682926 \\
b_{47} &= 542.9942625 \\
b_{48} &= -85.66878481 \\
c_0 &= 0.08104183147 \\
c_1 &= -0.4513858027 \\
c_2 &= 0.8057261332 \\
c_3 &= -0.4668315566 \\
c_{31} &= 3.388557894 \times 10^5 \\
c_{32} &= 576.8 \\
c_{33} &= 0.206 \\
c_{40} &= 1.017179024 \\
d_{31} &= 2.100200454 \times 10^{-6} \\
d_{32} &= 23.94 \\
d_{33} &= 3.458 \\
d_{34} &= 13.6323539 \\
d_{35} &= 0.0136 \\
d_{36} &= 7.8526 \times 10^{-3} \\
e_1 &= 50.60225796 \\
e_2 &= -105.6677634 \\
e_3 &= 55.96905687
\end{align*}
\]

**Thermal Conductivity - Anomalous Region**

The Senger technique (ref. 12) as modified in reference 13 and again herein is calculated for \( 0.4 \leq \rho/\rho_c \leq 1.6 \). Let

\[
X^\beta = \left( \begin{array}{c}
1 - \frac{T}{T_c} \\
1 - \frac{\rho}{\rho_c} \\
\end{array} \right)^{0.35}
\]
and $\lambda_F$ represent the nonanomalous or frozen thermal conductivity. For $X^\beta < 0.4$, 

$$
\lambda - \lambda_F = \frac{11.6 \times 10^{-5}}{\sqrt{\rho} \left| 1 - \frac{\rho}{\rho_c} \right|^{1.71}}
$$

(B60)

For $X^\beta > 3$,

$$
\lambda - \lambda_F = \frac{11.6 \times 10^{-5}}{\sqrt{\rho} \left| 1 - \frac{T}{T_c} \right|^{0.6}}
$$

(B61)

For $0.4 \leq X^\beta \leq 3$,

$$
\lambda - \lambda_F = \frac{11.6 \times 10^{-5} X_0}{10 \sqrt{\rho} \left| 1 - \frac{T}{T_c} \right|^{0.6}}
$$

(B62)

where

$$
X_0 = \sum_{i=0}^{4} a_i \zeta^i
$$

(B63)

and

$$
\zeta = \log_{10} X^\beta
$$

$$
\begin{align*}
a_0 &= -0.17384732 \\
a_1 &= 0.82350372 \\
a_2 &= -1.55213983 \\
a_3 &= -0.12626138 \\
a_4 &= 2.83922425
\end{align*}
$$
Surface Tension and the Laplace Constant

Surface tension is given by

\[ \sigma = \frac{a_1(T - T_{c})^2}{1 - 0.83(T - T_{c})} + \sum_{i=2}^{5} \frac{a_i(T - T_{c})^i}{i!} \]  \hspace{1cm} (B64)

where

\begin{align*}
a_1 &= 0.1160936807 \\
a_2 &= 1.121404688 \times 10^{-3} \\
a_3 &= 5.75280518 \times 10^{-6} \\
a_4 &= 1.28627465 \times 10^{-8} \\
a_5 &= 1.149719240 \times 10^{-11}
\end{align*}

The Laplace constant is

\[ L = \sqrt{\frac{\sigma}{g(\rho_L - \rho_V)}} \]  \hspace{1cm} (B65)

where \( g \) is the local acceleration. If \( g \) is the acceleration of gravity,

\[ g = 980.665 \text{ cm/sec}^2 \]  \hspace{1cm} (B66)
APPENDIX C

DESCRIPTION OF IMPORTANT SUBROUTINES IN WASP

This appendix includes a discussion of the input/output and important features of the major subroutines in WASP. The method of solution used for the equations is indicated. The equation numbers refer to equations presented in appendix B. The FORTRAN IV variables mentioned correspond to the program listing in appendix E. The shorter subroutines not included in appendix C are completely described by comments in the listing in appendix E. Subroutine WASP has been described in the main text, in tables I and II; hence, the reader is assumed to be familiar with subroutine WASP.

MATHEMATICAL ROUTINES

The mathematical routines are as follows:

1. Function SOLVE (X₁, F, DF): This routine performs a Newton-Raphson iteration given the initial estimate X₁, the function F, and the derivative function DF. The convergence is determined when \( |(X_N - X_{N-1})/X_N| < TOL \). The value of TOL is 1. E-5 for iterations 1 to 40, 1. E-4 for 41 to 60, 1. E-3 for 61 to 80, and 1. E-2 for 81 to 100. In all cases studied the convergence was usually obtained in fewer than 40 iterations. For the exceptions, usually in the near-critical region of the PVT surface, the values returned with the increased tolerance are the best obtainable using equation (B3). The maximum number of iterations is 100, and an appropriate message is written if this number is reached.

2. Subroutines ROOT (X₀, X₂, FOFX, FUNC, X₁) and ROOTX (X₀, X₂, FOFX, FUNC, X₁): These two routines are identical except for name. The duplication is necessary for the double iterations in the solutions for temperature and density given pressure and enthalpy (KS=4) or pressure and entropy (KS=5) as input. (See also table I.) The solution method is a modified half-interval search technique for a monotonic function, FUNC, with a root between X₀ and X₂ such that \( FUNC(X₁) = FOFX \) where X₁ is the answer returned. The number of iterations does not exceed 100, and the tolerance is varied in the same manner as in function SOLVE. In addition, both the root and the function value FUNC(X₁) must meet a tolerance. While the tolerance on X₁ is TOL, the tolerance on FUNC(X₁) is 10*TOL. Error messages are written when the iterations reach 100 or when there is no solution in the interval X₀ to X₂.
Q-FUNCTIONS

These routines use D and TAU in program units of KU=1. Entry points with TAU as input indicate an iteration where D is known, while entry points with D and TAU as input are used in solving for D and in calculating all derived properties.

The Q-functions are as follows:

1. Function QMUST(D) calculates summation terms involving D needed by other Q-functions and stores them in COMMON/QAUX/ and /QSI/. ENTRY QMUST2(TAU) calculates summation terms involving TAU and stores them in /QAUX/.
2. Function QCALC(TAU) calculates equation (B4).
3. Function QT(D, TAU) calculates equation (B8).
4. Function QDTA(TAU) and ENTRY QDT(D, TAU) calculate equation (B9).
5. Function Q2DTA(TAU) and ENTRY Q2DT(D, TAU) calculate equation (B10).
6. Function Q2D2TA(TAU) and ENTRY Q2D2T(D, TAU) calculate equation (B11).
7. Function Q2T2D(TAU) calculates equation (B12).

FUNCTION CHECK

Function CHECK includes

1. ENTRY TCHECK (KU, KR, T)
2. ENTRY PCHECK (KU, KR, P)
3. ENTRY DCHECK (KU, D)

These entry points convert the variables from the user's units to the program's units, represented by KU=1, and check for out-of-range variables. Appropriate messages are written for any out-of-range input, but the calculation is allowed to continue.

The following subroutines use the mathematical routines, the Q-functions, function CHECK, and the subroutines listed with each in table V. The use of these subroutines is determined by the KS and KP options (see table I) and are called by subroutine WASP. If a user wants to use only a few of these subroutines, he can disassemble the WASP program by following the instructions in appendix D and the discussion for the routine of interest. Subroutine WASP uses the temperature parameter TAU (in user's units) for input to the subroutines. All the derived thermodynamic property and transport property subroutines assume that TAU, P, and D have been previously calculated. These subroutines are called twice by WASP for saturation properties, once with DL and once with DV as input for D.
SUBROUTINES TO OBTAIN STATE VARIABLES (KS OPTIONS)

The subroutines used to obtain the state variables are as follows:

(1) Subroutine DENS (KU, TAU, P, D, DL, DV, KR): This routine solves equation (B13) for the density, given TAU and P in units indicated by KU. The region number (KR) is returned, and the density is returned in D for KR=2 or KR=3. For KR=1, the saturation values are returned in DL and DV. If KR=1 for input and either TAU=0 or P=0 for input, the saturated value is calculated and returned for the variable which was input as 0.

The solution is obtained by ROOT for subcritical pressures and by SOLVE for saturation or supercritical pressures. Special initial estimates were found necessary for convergence near subcritical temperatures with SOLVE and for the interval used by ROOT in the region \( P > P_c \) and \( 373.15 \, \text{K} < T < 453.15 \, \text{K} (100^\circ \text{C} < t < 180^\circ \text{C}) \).

(2) Subroutine PRESS (KU, TAU, D, P, KR): This routine calculates pressure (eq. (B13)) as a function of TAU and D in regions KR=2 and KR=3 and as a function of TAU only in region KR=1 (using subroutine PSSS). The result, P, is returned in user's units indicated by KU. The correct value of KR is also returned and the calculation is direct.

(3) Subroutine TEMP (KU, P, D, TAU, KR): This routine solves equation (B13) for the temperature parameter TAU, given P and D in user's units specified by KU. In regions KR=2 and KR=3, SOLVE is used to obtain the solution. In region KR=1, which is either input or determined, TAU is a function of P only and is obtained from subroutine TSS by solving equation (B31) for TAU. Subroutine TSS also uses SOLVE. The correct KR is returned.

(4) Subroutine TEMPPH (KU, P, H, TAU, D, DL, DV, KR): This routine solves equation (B13) by using equation (B20) for the temperature parameter TAU and density D, given P and H as input in user's units indicated by KU. The double iteration is performed by using ROOT and ROOTX with function TSHF for regions KR=2 and KR=3. In region KR=1, the saturation values are determined for DL and DV by DENS, and TAU is found by function TSS (using SOLVE). KR is also returned.

(5) Subroutine TEMPPS (KU, P, S, TAU, D, DL, DV, KR): This routine solves equations (B13) and (B24) for TAU and D in the same manner as TEMPPH, using P and S as input and function TPSF for the double iteration with ROOT and ROOTX.

SUBROUTINES TO OBTAIN DERIVED THERMODYNAMIC PROPERTIES

The subroutines used to obtain derived thermodynamic properties assume that the variables TAU and D have been input or previously calculated in the user's units. This condition is satisfied in subroutine WASP. When KR=1 is input or has been so deter-
mined, subroutine WASP makes two calls to each routine, once using DL and once DV for input D; and the corresponding saturated variable is output [(HL, SL, etc.), (HV, SV, etc.)].

These subroutines are as follows:

1. Subroutine ENTH (KU, TAU, D, H): This routine calculates enthalpy H in user's units (KU) by using equation (B20).

2. Subroutine ENT (KU, TAU, D, S): This routine calculates entropy S in user's units (KU) by using equation (B24).

3. Subroutine CPPRL (KU, TAU, D, CP, CV, GAMMA, C): This routine calculates the following in user's units indicated by KU:
   - Specific heat at constant pressure, CP, eq. (B27)
   - Specific heat at constant volume, CV, eq. (B26)
   - Specific-heat ratio, GAMMA, eq. (B28)
   - Sonic velocity, C, eq. (B30)

In addition, the first partial derivatives of P are calculated and returned in COMMON/PARTLS/PTV, PDT in the units of KU=1 only. PTV is equation (B16) and PDT is equation (B14).

SUBROUTINES TO OBTAIN TRANSPORT PROPERTIES

The three routines used to obtain the transport properties assume that the input variables for pressure and density and the temperature parameter \( \tau \) are all available in user's units. They are called twice by WASP for saturation conditions, once with DL and once with DV as input for density DIN.

1. Subroutine VISC (KU, KR, TIN, PIN, DIN, SVISC): This routine uses TIN, PIN, and DIN as input in user's units KU. Dynamic viscosity, SVISC, is calculated by using one or more of equations (B32) to (B39), depending on the region of the input variables as shown in figure 1 and explained in appendix B. All calculations of dynamic viscosity are direct evaluations of curve fits.

2. Subroutine THERM (KU, KR, TIN, PIN, DIN, EXCESK, TCOND): This routine uses TIN, PIN, and DIN in user's units KU to calculate the thermal conductivity TCOND in user's units KU. An optional coding section calculates the critical excess thermal conductivity associated with the critical anomaly in the PVT region, \( 0.6 < \rho / \rho_c < 1.4 \) and \( 0.9 < T/T_c < 1.1 \). See also references 12, 13, and 15 and the subroutine listing in appendix E.

The equations used for thermal conductivity are (B40) to (B59) for the different regions as shown in figure 2. The equation for region IV (eq. (B52)) is iterative. The thermal conductivity for the other regions is calculated by direct evaluation of curve fits.
(3) Subroutine SURF (KU, KR, TIN, SURFT): This routine uses TIN, the input temperature parameter, in user's units, to calculate both the surface tension of liquid water and the Laplace constant. The calculated surface tension is returned in SURFT, and the Laplace constant (ALC) is returned in COMMON/LAPLAC/ALC. The statement COMMON/LAPLAC/ALC must appear in the user's calling routine if the Laplace constant is desired.
APPENDIX D

MODULAR DESIGN OF WASP

A user with limited core storage or with specific property needs may wish to use only parts of WASP. The subroutines have been coded so that most of the subroutines corresponding to the "KP option" requests may be removed without causing errors in logic or calculations. Table V indicates which routines are absolutely necessary and which are optional. The conditions for removal must be strictly followed. For simplicity, the KP options are discussed as though only one option was being requested. In reality, the input variable KP is always the summation of the KP option variables. To modify a statement number in subroutine WASP, simply replace it with a continue statement of the same number. For example, to remove the viscosity option, remove subroutine VISC. In subroutine WASP, alteration would read as follows:

160 CONTINUE
170 DO 175 I=1, 32

If the user wishes to omit many options, he should rewrite subroutine WASP for efficiency.
APPENDIX E

PROGRAM LISTING AND FLOW CHART FOR SUBROUTINE WASP

PROGRAM LISTING

C $HTIC AQUA
C SUBROUTINE WASP (KS, KP, TT, P, O, H, KR)
C
C KEYFS KENNAN HILL MOORE EQUATION OF STATE FOR WATER
C
C ---------------------------VERSION MARCH 1, 1972---------------------
C
C COMPUTE THE STATE RELATIONS AND THERMODYNAMIC AND TRANSPORT
C PROPERTIES OF WATER GIVEN TEMPERATURE TT, PRESSURE P,
C DENSITY O, OR ENTHALPY H, OR ENTROPY S. STATE RELATIONS ARE
C SPECIFIED BY KS. THERMODYNAMIC AND TRANSPORT PROPERTIES
C ARE SPECIFIED BY KP. IF KR IS RETURNED OR SPECIFIED AS 1,
C PROPERTIES ARE COMPUTED AT SATURATION.
C
C COMMON/PROPERTY/KU, DL, DV, HL, HV, S, SL, SV, CV, CVL, CvV, CP, CPL, CPV, GAMMA,
C 1GAMMA, 1GAMMA, 1GAMMA, 1GAMMA, 1GAMMA, 1GAMMA, 1GAMMA, 1GAMMA, 1GAMMA,
C REAL M1, MUL, MUV, K1, KLV
C COMMON/ CHECKS/DCH1, DCH2, PCH1, PCH2, PCH3, TCH1, TCH2, TCH3, DST, TST, H
C ISCH1, MSHC2
C
C TAU IS THE TEMPERATURE PARAMETER USED IN THE EQUATION OF STATE
C TAU IS EQUIVALENT TO T IN THIS SUBROUTINE
C
C DIMENSION KPC1(32), KPC2(32), KPC3(32), KPC4(32)
C DATA KPC1 /23, 36, 7, 10, 11, 14, 15, 18, 19, 22, 23, 26, 27, 30, 31, 34, 35, 38,
C 139, 42, 43, 46, 47, 50, 51, 54, 55, 58, 59, 62, 63/
C DATA KPC2 /145, 67, 7, 12, 13, 14, 15, 20, 21, 22, 23, 28, 29, 30, 31, 36, 37, 38,
C 139, 44, 45, 47, 52, 53, 54, 55, 60, 61, 62, 63/
C DATA KPC3 /8, 9, 10, 11, 12, 13, 14, 15, 24, 25, 26, 27, 28, 29, 30, 31, 40, 41, 42,
C 143, 44, 45, 46, 55, 56, 57, 58, 59, 60, 61, 62, 63/
C DATA KPC4 /16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31,
C 148, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63/
C T=TT
C IF (TT.GT.0.) T=1000./TT
C GO TO (10, 20, 30, 40, 45), KS
C
C COMPUTE DENSITY
C
C 10 CALL DENS(KS, TT, P, O, DL, DV, KR)
C IF (TT.EQ.0.0) TT=1000./T
C GO TO 50
C COMPUTE PRESSURE
C
20 CALL PRESS(KU,T,D,P,KR)
GO TO 50
C
C COMPUTE TEMPERATURE
C
30 CALL TEMPI(KU,P,O,T,KR)
TT=1000°/T
GO TO 50
C
C COMPUTE TEMPERATURE AND DENSITY GIVEN PRESSURE AND ENTHALPY
C
40 CALL TEMPPH(KU,P,H,T,D,DL,DV,KR)
TT=1000°/T
GO TO 50
45 CALL TEMPPS(KU,P,S,T,D,DL,DV,KR)
TT=1000°/T
50 IF (KR .NE. 1 OR (KS .EQ. 1 OR KS .GT. 3)) GO TO 55
C
C OBTAIN SATURATION DENSITIES DL AND DV FOR KS=2 AND KS=3 CALLS WHEN
C KR=1
C
CALL DENS(KU,T,P,O,DL,DV,1)
55 IF (MOD(KP,2))160,70,60
C
C COMPUTE ENTHALPY
C
60 IF (KR .EQ. 1) GO TO 65
CALL ENTH(KU,T,O,H)
GO TO 70
65 CALL ENTH(KU,T,DL,HL)
CALL ENTH(KU,T,DL,HV)
70 DO 80 I=1,32
IF (KP .EQ. IC) 110,100,80
80 CONTINUE
GO TO 110
C
C COMPUTE ENTROPY
C
100 IF (KR .EQ. 1) GO TO 105
CALL ENTI(KU,T,O,S)
GO TO 110
105 CALL ENTI(KU,T,DL,SL)
CALL ENTI(KU,T,DL,SV)
110 DO 120 I=1,32
IF (KP .EQ. IC) 140,130,120
120 CONTINUE
GO TO 140
C
C COMPUTE SPECIFIC HEATS AND GAMMA AND SONIC VELOCITY
C
130 IF (KR .EQ. 1) GO TO 135
CALL CPPRL(KU,T,DL,CPL,CVL,GAMHL,CL)
CALL CPPRL(KU,T,DL,CPV,CVVM,GAMHV,CVP)
GO TO 140
135 CALL CPPRL(KU,T,O,CP,CV,GAMMA,C)
140 DO 150 I=1,32
IF (KP .EQ. IC) 170,160,150
150 CONTINUE
GO TO 170
COMPUTE VISCOSITY

160 IF (KR.NE.1) GO TO 165
    CALL VISC(KU,KR,T,P,DL,MUL)
    CALL VISC(KU,KR,T,P,DU,MUV)
    GO TO 170
165 CALL VISC(KU,KR,T,P,DU,MU)
170 DO 175 I=1,32
175 CONTINUE
    GO TO 190

COMPUTE THERMAL CONDUCTIVITY

180 IF (KR.NE.1) GO TO 220
    CALL THERM(KU,KR,T,DL,EXCL,KL)
    CALL THERM(KU,KR,T,DU,EXCV,KV)
    GO TO 190
220 CALL THERM(KU,KR,T,DU,EXCESK,K)
190 IF (KP-32) 230,240,240

COMPUTE SURFACE TENSION

240 CALL SURF(KU,KR,T,SIGMA)
230 RETURN
END
C

ERROR CHECKS/DCH1,DCH2

COMMON /COSAT/CPS1, CPS2, CPS4, CPS5, CPS6, CPS7/

CPS1 /SICOF/ SIC1,SIC2,SIC3,SIC4,SIC5

COMMON /CONV1/DCONV(5)

COMMON /CONV2/DCONV(5)

COMMON /CONV3/DCONV(5)

COMMON /CONV4/DCONV(5)

COMMON /CONV5/DCONV(5)

COMMON /CONV6/DCONV(5)

COMMON /CONV7/DCONV(5)

COMMON /CONV8/DCONV(5)

COMMON /CONV9/DCONV(5)

REAL DCONV(2)

DATA A1,..SIC(5),..SIC(5)

DATA A2,..SIC(5),..SIC(5)

DATA A3,..SIC(5),..SIC(5)

DATA A4,..SIC(5),..SIC(5)

DATA A5,..SIC(5),..SIC(5)

DATA A6,..SIC(5),..SIC(5)

DATA A7,..SIC(5),..SIC(5)

DATA A8,..SIC(5),..SIC(5)

DATA A9,..SIC(5),..SIC(5)

DATA A10,..SIC(5),..SIC(5)

DATA A11,..SIC(5),..SIC(5)

DATA A12,..SIC(5),..SIC(5)

DATA A13,..SIC(5),..SIC(5)

DATA A14,..SIC(5),..SIC(5)

DATA A15,..SIC(5),..SIC(5)

DATA A16,..SIC(5),..SIC(5)

DATA A17,..SIC(5),..SIC(5)

DATA A18,..SIC(5),..SIC(5)

DATA A19,..SIC(5),..SIC(5)

DATA A20,..SIC(5),..SIC(5)

DATA A21,..SIC(5),..SIC(5)

DATA A22,..SIC(5),..SIC(5)

DATA A23,..SIC(5),..SIC(5)

DATA A24,..SIC(5),..SIC(5)

DATA A25,..SIC(5),..SIC(5)

DATA A26,..SIC(5),..SIC(5)

DATA A27,..SIC(5),..SIC(5)

DATA A28,..SIC(5),..SIC(5)

DATA A29,..SIC(5),..SIC(5)

DATA A30,..SIC(5),..SIC(5)

DATA A31,..SIC(5),..SIC(5)

DATA A32,..SIC(5),..SIC(5)

DATA A33,..SIC(5),..SIC(5)

DATA A34,..SIC(5),..SIC(5)

DATA A35,..SIC(5),..SIC(5)

DATA A36,..SIC(5),..SIC(5)

DATA A37,..SIC(5),..SIC(5)

DATA A38,..SIC(5),..SIC(5)

DATA A39,..SIC(5),..SIC(5)

DATA A40,..SIC(5),..SIC(5)

DATA A41,..SIC(5),..SIC(5)

DATA A42,..SIC(5),..SIC(5)

DATA A43,..SIC(5),..SIC(5)

DATA A44,..SIC(5),..SIC(5)

DATA A45,..SIC(5),..SIC(5)

DATA A46,..SIC(5),..SIC(5)

DATA A47,..SIC(5),..SIC(5)

DATA A48,..SIC(5),..SIC(5)

DATA A49,..SIC(5),..SIC(5)

DATA A50,..SIC(5),..SIC(5)

DATA A51,..SIC(5),..SIC(5)

DATA A52,..SIC(5),..SIC(5)

DATA A53,..SIC(5),..SIC(5)

DATA A54,..SIC(5),..SIC(5)

DATA A55,..SIC(5),..SIC(5)

DATA A56,..SIC(5),..SIC(5)

DATA A57,..SIC(5),..SIC(5)

DATA A58,..SIC(5),..SIC(5)

DATA A59,..SIC(5),..SIC(5)

DATA A60,..SIC(5),..SIC(5)

DATA A61,..SIC(5),..SIC(5)

DATA A62,..SIC(5),..SIC(5)

DATA A63,..SIC(5),..SIC(5)

DATA A64,..SIC(5),..SIC(5)

DATA A65,..SIC(5),..SIC(5)

DATA A66,..SIC(5),..SIC(5)

DATA A67,..SIC(5),..SIC(5)

DATA A68,..SIC(5),..SIC(5)

DATA A69,..SIC(5),..SIC(5)

DATA A70,..SIC(5),..SIC(5)

DATA A71,..SIC(5),..SIC(5)

DATA A72,..SIC(5),..SIC(5)

DATA A73,..SIC(5),..SIC(5)

DATA A74,..SIC(5),..SIC(5)

DATA A75,..SIC(5),..SIC(5)

DATA A76,..SIC(5),..SIC(5)

DATA A77,..SIC(5),..SIC(5)

DATA A78,..SIC(5),..SIC(5)

DATA A79,..SIC(5),..SIC(5)

DATA A80,..SIC(5),..SIC(5)

DATA A81,..SIC(5),..SIC(5)

DATA A82,..SIC(5),..SIC(5)

DATA A83,..SIC(5),..SIC(5)

DATA A84,..SIC(5),..SIC(5)

DATA A85,..SIC(5),..SIC(5)

DATA A86,..SIC(5),..SIC(5)

DATA A87,..SIC(5),..SIC(5)

DATA A88,..SIC(5),..SIC(5)

DATA A89,..SIC(5),..SIC(5)

DATA A90,..SIC(5),..SIC(5)

DATA A91,..SIC(5),..SIC(5)

DATA A92,..SIC(5),..SIC(5)

DATA A93,..SIC(5),..SIC(5)

DATA A94,..SIC(5),..SIC(5)

DATA A95,..SIC(5),..SIC(5)

DATA A96,..SIC(5),..SIC(5)

DATA A97,..SIC(5),..SIC(5)

DATA A98,..SIC(5),..SIC(5)

DATA A99,..SIC(5),..SIC(5)

DATA A100,..SIC(5),..SIC(5)
SUBROUTINE ROOTXIXOtX2.FOFX.FUNC,X,I,i
SOLVE FOR X1 SUCH THAT FUNC(X1) = FOFX, WHERE X1 LIES BETWEEN X0 AND X2
COMMON /CHECK2/KOUNT
TOL=1.0.E-5
XX0 = X0
XX2 = X2
F0 = FUNC(XX0)
F2 = FUNC(XX2)
A=(FOFX-F0)/(F2-F0)
IF (A) 1007,120,120
120 IF (A-1.) 130,130,1008
130 IF (FOFX-0.) 80,70,80
70 ASSIGN 100 TO JUMP
GO TO 90
80 ASSIGN 110 TO JUMP
90 X = (XX0+XX2)/2.
KOUNT = 0
150 X1 = X
KOUNT = KOUNT + 1
A = FOFX - F2
FX = FUNC(X)
FXX=FOFX-1(F2-F0)/(XX2-XX0)
8=ABS((FX-XXX)/(F2-F0))
IF (A*FX-FOFX) .LT. 0.) GO TO 1001
XX0 = X
FX=FX
IF (B-.3) 10,20,20
20 X = (XX0+XX2)/2.
GO TO 40
1001 XX2 = X
F2 = FX
IF (B-.3) 10,30,30
30 X = (XX0+XX1)/2.
GO TO 40
10 X=XX0+(FOFX-F0)*(XX2-XX0)/(F2-F0)
40 IF (ABS(X-X1)/X) .LT. 0.) GO TO 1001
50 GO TO JUMP,(100,110)
100 IF (ABS(FUNC) .LT. 10.-60,1000,1000
110 IF (ABS(FUNCFX)/FOFX) .LT. 60,1000,1000
1000 IF (KOUNT-60) TOL=TOL+10.
IF (KOUNT-60) TOL=TOL+10.
IF (KOUNT-60) TOL=TOL+10.
IF (KOUNT-100) GO TO 150
150 WRITE (6,170) X1,X
170 FORMAT (1HL,75HAN ITERATION HAS BEEN TERMINATED AT 100 ITERATIONS.
1 THE LAST TWO VALUES WERE .3GL5.5)
SUBROUTINE ROOT (X0, X2, FOFX, FUNC, XI)

C
C ------------------------ VERSION 2/1/72 ------------------------
C
C SAME AS ROOTX - NEEDED TO PREVENT RECURSION
C
C SOLVE FOR XI SUCH THAT |FUNC(XI)| = FOFX, WHERE XI LIES
C BETWEEN X0 AND X2
C
COMMON /CHECK1/KOUNT
TOL=1.E-5
X0 = X0
X2 = X2
FO = FUNC(X0)
F2 = FUNC(X2)
A=(FOFX-FO)/(F2-F0)
IF (A) 1007.120.120
120 IF (A-1.*) 130.130.1008
130 IF (FOFX-0.*) 80.70.80
70 ASSIGN 100 TO JUMP
GO TO 90
80 ASSIGN 110 TO JUMP
90 X = (X0*X2)/2.
KOUNT = 0
150 XI = X
   KOUNT = KOUNT + 1
   A = FOFX - F2
   FX = FUNC(X)
   FXL=FO+(X-X0)*(F2-FO)/(X2-X0)
   B=ABS((FX-FXL)/(F2-FO))
   IF (A*(FX-FOFX) .LT. 0.) GO TO 1001
   XX0 = X
   FO=FX
   IF (B-.31 10,20.20
20 X = ((XI+XX2)/2.
   GO TO 40
1001 XX2 = X
   F2 = FX
   IF (B-.31 10,30.30
30 X = ((X0*X)/2.
   GO TO 40
1C X=XX0+(FCFX-F0)*(XX2-XX0)/(F2-F0)
40 IF (ABS((X-XI)/X)-TOL ) 50.1000.1000
50 GO TO JUMP.(100.110)
100 IF (ABS(FUNC(X))=TOL*10. 160.1000.1000
110 IF (ABS((FOFX-FUNC(X))/FOFX)-TOL ) 60.1000.1000
1000 IF (KOUNT=GT.40) TOL=TOL*10.
   IF (KOUNT=GT.60) TOL=TOL*10.
   IF (KOUNT=GT.80) TOL=TOL*10.
   IF (KOUNT=LT.100) GO TO 150
16C WRITE (6,170) XI,X
170 FORMAT (1HL,79LMAN ITERATION HAS BEEN TERMINATED AT 100 ITERATIONS.
1 THE LAST TWO VALUES WERE .3615.5)
1 6C XI=X
RETURN
1007 XI = X0
GO TO 140
1008 XI = X2
140 WRITE(6,141)
141 FORMAT(1HM0.24H SOLUTION OUT OF RANGE)
RETURN
END
FUNCTION SOLVE(XI,F,DF)

NEWTON-RAPHSON ITERATION GIVEN AN INITIAL ESTIMATE XI
AND THE FUNCTIONS F AND DF

COPMGN /CHECK1/N
TOL=1.E-5
N1=0
X0=XI
XN=XI

10 X00=X0
XG=XN
XN=XM-F(XO)/DF(XO)

IF (ABS((XN-XO)/XN)-TOL ) 70,20,20

20 IF (NI.GT.40) TOL=TOL*10.
    IF (NI.GT.60) TOL=TOL*10.
    IF (NI.GT.80) TOL=TOL*10.
    IF (NI-100) 30,50,50

30 IF (ABS((XN-X00)/XN)-TOL ) 40,10,10
40 XN=(XO+XN)/2.

GO TO 10

50 WRITE (6,60) X00, XO, XN

60 FORMAT (1HL,80HAN ITERATION HAS BEEN TERMINATED AT 100 ITERATIONS.
     1 THE LAST THREE VALUES WERE ,3G15.5)

70 SOLVE=XN
RETURN
END
FUNCTION CHECK(\text{KU, KR, T})

---------------VERSION MARCH 1, 1972---------------

COMMON/CCNV1/DCONV(5)
COMMON/CCNV2/TCONV(5)
COMMON/CCNV3/PCONV(5)
COMMON/IERORD/ IROUT
COMMON/CHECKS/DCH1,DCH2,PCH1,PCH2,PCH3,TCH1,TCH2,TCH3,ST,TST,
IHSCH1,TSCCH2
DIMENSION FM1(9), FM2(9), FM3(9), FMT(9), ROUT(11)
DATA FM1 /51H(1H ,G12•4 ,31HIS OUT OF RANGE FOR T IN SUB.--,A6 ) /
 DATA FM2 /51H(1H ,G12•4 ,31HIS OUT OF RANGE FOR P IN SUB.--,A6 ) /
 DATA FM3 /51H(1H ,G12•4 ,31HIS OUT OF RANGE FOR D IN SUB.--,A6 ) /
 DATA ROUT /4HDENS,5HPRESS,4HTEMP,4HENT,3HEN,T,6HTEMPPH,6HTEMPPS
1,5HCPPRL,4HVISC,5HTHERM,4HSURF/

CONVERT TEMPERATURE T TO DEGREES KELVIN AND CHECK
FOR OUT OF RANGE. UNITS ARE SPECIFIED BY KU. IF KR
IS SPECIFIED AS 1, T IS CHECKED FOR OUT OF SATURATION

ENTRY TCHECK(KU,KR,T)
CHECK=1000*TCONV(KU)/T
CH1=1000./TCH3
CH2=1000./TCH2
CH3=1000./TCH1
KODE=1
DO 1 J=1,9
1 FMT(J)=FM1(J)
GO TO 10

CONVERT PRESSURE TO MP/MP**2 AND CHECK
FOR OUT OF RANGE. UNITS ARE SPECIFIED BY KU. IF KR IS
SPECIFIED AS 1, P IS CHECKED FOR OUT OF SATURATION

ENTRY PCHECK(\text{KU, KR, P})
CHECK=P/PCONV(KU)
CH1= PCH1
CH2= PCH2
CH3= PCH3
KODE=0
DO 2 J=1,9
2 FMT(J)=FM2(J)
GO TO 10

CONVERT DENSITY TO G/CC AND CHECK
FOR OUT OF RANGE. UNITS ARE SPECIFIED BY KU.

ENTRY DCHECK(\text{KU, D})
CHECK =D/DCGNV(KU)
CH1=DCH1
CH3=DCH2
KODE=0
DO 3 J=1,9
3 FMT(J)=FM3(J)
GO TO 20
10 IF(KR.EQ.1) GO TO 30
20 IF (CHECK LT CH1) GO TO 40
   IF (CHECK GT CH3) GO TO 40
25 IF (KODE EQ 1) CHECK = T/TCONV(KU)
   RETURN
30 IF (CHECK LT CH1) GO TO 40
   IF (CHECK LE CH2) GO TO 25
40 WRITE(6, FMT) CHECK, ROUT IREUT)
   GO TO 25
   ENC

SUBROUTINE CMUST(D)

C  ___________________________VERSION MARCH 1, 1972___________________________

COMMON /CCNSTS/ TAU0, RHOA, RHOB, TAU0, E, R
COMMON /OAUX/ RBDIF(8), RADIF(8), ER, ED, TADIF(7)
COMMON /COF/ A(10,7)
COMMON/QSI/SUMI(17)
RADIF (1) = 1.0
RADIF (2) = D - RHOA
RBDIF (1) = 1.0
RBDIF (2) = D - RHOA
DO 1 I = 3, 8
RBDIF (I) = RBDIF (I-1) * RBDIF (2)
1 RADIF (I) = RADIF (I-1) * RADIF (2)
   ED = E*D
   ER = 1.0/EXP(ED)
   SUMI(1) = 0.0
   DO 4 I = 1, 8
4 SUMI(I) = SUMI(I) + A(I, I) * RADIF(I)
   SUMI(I) = SUMI(I) + ER * (A(9, I) + A(10, I) * D)
   DC 6 J = 2, 7
   SUMI(J) = 0.0
   DO 5 I = 1, 8
5 SUMI(J) = SUMI(J) + A(I, J) * RBDIF(I)
   SUMI(J) = SUMI(J) + ER * (A(5, J) + A(10, J) * D)
   CONTINUE
   ENTRY GMUST2(TAU)
   TADIF (1) = 0.0
   TADIF (2) = 1.0
   TADIF (3) = TAL - TAU0
   DO 2 I = 4, 7
2 TADIF (I) = TADIF (I-1) * TADIF (3)
   RETURN
   ENC
SINFTC SUB2
FUNCTION QCALC(TAU)
C ---------------VERSION MARCH 1,1972-------------
C THE FUNCTION Q(RHO,TAU)
C
COMMON/CHECKS/DCH1,DCH2,PCH1,PCH2,PCH3,TCH1,TCH2,TCH3,DST,TST, 1HSCH1,HSCH2
COMMON /GAUX/ RBDIF(8),RADIF(8),ER,ED,TADIF(7)
COMMON /COF/ A(10,7)
COMMON/GSI/SUMI(7)
TSUM = 0.0
DO 4 J=2,7
4 TSUM=TSUM+TADIF(J)*SUMI(J)
QCALC=SUMI(1)+(TAN-TCH2)*TSUM
RETURN
END

SINFTC SUB3
FUNCTION QOTA(TAU)
C ---------------VERSION MARCH 1,1972-------------
C
C PARTIAL DERIV OF Q --- PQ/PRHO
COMMON /GAUX/ RBDIF(8),RADIF(8),ER,ED,TADIF(7)
COMMON /COF/ A(10,7)
COMMON /CONSTS/ TAUC,RHOA,RHOB,TAA,U,E,R
COMMON/XMINUS/XMI(7)
COMMON/OS2/SUMI(7)
EQUIVALENCE (SUMI(1),SUM)
1 TSUM=0.0
DO 2 J=2,7
2 TSUM=TSUM+TADIF(J)*SUMI(J)
QOTA=SUM+(TAU-TAUC)*TSUM
RETURN
ENTRY QOTC(0,TAU)
SUM=0.0
DC 10 I=2,8
10 SUM=SUM*X1[I-1]*A(1,1)*RADIF(I-1)
SUM=SUM+ER*(A(10,1)-E*(A(9,1)+A(10,1)*D))
DC 15 J=2,7
SUM(J)=0.0
DC 12 I=2,8
12 SUM(J)=SUM(J)+X1[I-1]*A(1,J)*RBDIF(I-1)
SUM(J)=SUM(J)+ER*(A(10,J)-E*(A(9,J)+A(10,J)*D))
15 CONTINUE
GO TO 1
END
$\text{SUBS} 4$

\text{FUNCTION QTD(TAU)}

--- PARTIAL DER OF Q --- PQ/PTAU

\text{COMMON} /Q0UX/RBDIF(8),RADIF(8),ER,ED,TADIF(7)
\text{COMMON} /COF/ A(10,7)
\text{COMMON} /CCNST/TAUC,RH0A,RH0B,TAUA,E,R
\text{COMMON}/QST/SUM(7)
\text{COMMON}/XMINUS/XM(7)

TSM1 = 0.0
TSM2 = 0.0
DC 18 J=3,7
TSM1=TSUM1+XMI(J-2)*TADIF(J-1)*SUM(J)
TSM2=TSUM2+TADIF(J)*SUM(J)
QTO=TSUM2+(TAU-TAUC)*TSUM1
RETURN
END

$\text{SUBS} 5$

\text{FUNCTION Q212O(TAU)}

--- PARTIAL DER OF Q --- P2O/PTAU2

\text{COMMON} /Q0UX/ RBDIF(8),RADIF(8),ER,ED,TADIF(7)
\text{COMMON} /COF/ A(10,7)
\text{COMMON} /CCNST/ TAUC,RH0A,RH0B,TAUA,E,R
\text{COMMON}/QST/SUM(7)
\text{COMMON}/XMINUS/XM(7)

TSM1 = 0.0
TSM2 = 0.0
DC 2 J=3,7
TSM1=TSUM1+XMI(J-2)*TADIF(J-1)*SUM(J)
IF (J.EQ.3) GO TO 2
TSM2=TSUM2+XMI(J-2)*XMI(J-3)*TADIF(J-2)*SUM(J)
2 CONTINUE
Q212=2.0*TSUM1+(TAU-TAUC)*TSUM2
RETURN
END
&IBFTC SUB6
  FUNCTION Q2DTA(TAU)
  C
  C ------------------------VERSION MARCH 1,1972------------------------
  C--- PARTIAL DER OF Q --- P2Q/PX0-PTAU
    COMMON /GAUX/ RXDIF(8),RADIF(8),ER,ED,TADIF(7)
    COMMON /COF/ A(10,7)
    COMMON /CONS/ TAUC,RHOA,RHOB,TAUA,E,R
    COMMON/Q53/SUM(6)
    COMMON/XMINUS/XM1(7)
  1 TSM1=0.0
     TSM2=0.0
     DO 10 J=3,7
       TSM1=TSUM1+XM1(J-2)*TADIF(J-1)*SUM(J-1)
  10 TSM2=TSUM2+TADIF(J)*SUM(J-1)
     TSM1=TSUM1+SUM(1)
     TSLM=TSUM1*(TAU-TAUC)
     Q2CTA=TSUM1+TSUM2
     RETURN
  ENTRY Q2DT(D,TAU)
     DO 20 J=2,7
       SUM(J-1)=0.
     DO 15 I=2,8
       SUM(J-1)=SUM(J-1)*ER*(A(I,J)-E*(A(I,J)+A(I,J)*D))
  15 CONTINUE
     GC TO 1
END

&IBFTC SUB7
  FUNCTION Q2DTA(TAU)
  C
  C ------------------------VERSION MARCH 1,1972------------------------
  C--- PARTIAL DER OF Q --- P2Q/PX0/P2
    COMMON /GAUX/ RXDIF(8),RADIF(8),ER,ED,TADIF(7)
    COMMON /COF/ A(10,7)
    COMMON /CONS/ TAUC,RHOA,RHOB,TAUA,E,R
    COMMON/Q54/SUM(7)
    COMMON/XMINUS/XM1(7)
  1 TSM1=0.0
     DO 5 J=2,7
       TSM1=TSUM+TADIF(J)*SUM(J)
     Q2CTA=SUM(1)+(TAU-TAUC)*TSUM
     RETURN
  ENTRY Q2DT(D,TAU)
     SUM(1)=0.0
     DO 3 I=3,8
       SUM(1)=SUM(1)+XM1(I-1)*XM1(I-2)*A(I,1)*RADIF(I-2)
     DO 10 J=2,7
       SUM(J)=0.0
     DO 8 I=3,8
       SUM(J)=SUM(J)+XM1(I-1)*XM1(I-2)*A(I,J)*RADIF(I-2)
     8 CONTINUE
     GC TO 1
END
SUBROUTINE PSSS(PSS)

--------------------VERSION MARCH 1, 1972--------------------

C COMPEE SATURATION PRESSURE PSSS IN BARS AS A FUNCTION OF T IN DEGREES
C C AND RETURN ANSWER IN PSS IN MM/M2
C
COMMON/COSAT/ CPS1 , CPS2, CPS3, CPS4, CPS5, CPS6, CPS7
C--- THE T IN THE COMMON BEND17 IS REALLY TAU
COMNM/TPARM/T
DIMENSION CTIPS(6)
DATA CTIPS / .31602383E-03, 1.00044775, -0.46487771E-05,
1 0.69431852E-08, 0.15621197E-12, 1.00043357 /
TSC = 1000./T -273.15
C--- CONVERT TSC(thermoregistic CELSIUS TO INT.PRACTICAL SCALE (C) WHICH
C-----IS USED IN SATURATION EQUATION
IF (TSC .GE. 9.996) GO TO 9
TS = CTIPS(6) * TSC
GO TO 10
9 TS = (((CTIPS(5)*TSC+CTIPS(4))*TSC + CTIPS(3)*TSC + 1CTIPS(2))
1 +TSC + CTIPS(1)
10 TS=TS+273.15
PSS=10.**(((CPS7*TS+CPS6)*TS+CPS5)*TS+CPS4)*TS+CPS3)*TS+CPS2/TS+
1CPS1)
PSS=PSS/10.0
RETURN
END

51
FUNCTION TSS(PS)

COMPUTE SATURATION TEMPERATURE IN DEG C AS A FUNCTION OF PRESSURE
IN BARS AND RETURN ANSWER TSS AS TAU IN KELVIN**1

COMMON/CHECKS/DCH1(1),DCH2,PCH1,PCH2,PCH3,TCH1,TCH2,TCH3,OST,TST,H
ISCH1,HECH2
COMMON/COSAT/ CPS1 ,CPS2,CPS3,CPS4,CPS5,CPS6,CPS7
COMMON/BEND9/A1,A2,A3,A4,A5
DIMENSION CTT(6)
DATA CTT = .30733645E-03, 0.99955209, 0.46490458E-05, -69336443E-08
   1.0, 0.18086305E-12, 0.99956709 /
EXTERNAL TSSF,DTSSF
PS1=PS*10.0
A1=CPS1-ALOG10(PS1)
A2=5.*CPS7
A3=4.*CPS6
A4=3.*CPS5
A5=2.*CPS4
TESTM = (1000./TCH2 -20.0 )
TSS=SOLVE(TESTM,TSSF,DTSSF)
TSS=TSS-273.15

C----CONVERT THE CALCULATED SATURATION TEMP. FROM INT. PRACTICAL SCALE
C------(C) TO THERMODYNAMIC CELSIUS SCALE

TSSP=TSS
IF (TSS .GT. 10.) GO TO 9
TSS = CTT(6)* TSS
GO TO 10
9 TSS = (((CTT(5)*TSS + CTT(4))*TSS + CTT(3))*TSS + CTT(2))*TSS +
   1
10 TSS = 1000./(TSS+273.15)
RETURN
END

SUBIO

FUNCTION TSSF(TSS)

FUNCTION USED TO SOLVE FOR SATURATION TEMPERATURE TSS

COMMON/COSAT/ CPS1 ,CPS2,CPS3,CPS4,CPS5,CPS6,CPS7
COMMON/BEND9/A1,A2,A3,A4,A5
TSSF=((CPS7*TSS+CPS6)*TSS+CPS5)*TSS+CPS4)*TSS+CPS3)*TSS+CPS2/ 
   ITSS+A1
RETURN
ENTRY DTSSF(TSS)

DERIVATIVE OF FUNCTION USED TO SOLVE FOR SATURATION
TEMPERATURE TSS GIVEN PRESSURE

TSSF=((A2*TSS+A3)*TSS+A4)*TSS+A5)*TSS+CPS3-CPS2/(TSS*TSS)
RETURN
END
SUBROUTINE PRESSIKU+T.OO.F+KRI

COMPUTE PRESSURE P GIVEN TEMPERATURE T AND DENSITY D.
UNITS ARE SPECIFIED BY KU. IF KR IS RETURNED OR
SPECIFIED AS 1, P IS COMPUTED AT SATURATION AS A
FUNCTION OF T ONLY.

COMMON /CONV3/PCONV(5)

COMMON /PARAM/TS

COMMON /COSTS/ TAU,C,MOA,RHOG,TAA,EA,R

COMMON/JOINS/DCH1,DCH2,PCH1,PCH2,PCH3,TCH1,TCH2,TCH3,OSE,TS

COMMON/REGION/TS,TCHEC,IKU,DC

COMMON/ERROR/IROUT

IROUT=2

TS=TCHEC(KU,KR,T)

DETERMINE REGION

IF (KR-1) 10.70.10

10 DS=DCHECK(KU,D)

IF (KR - GT 1) GO TO 80

IF (TS-TCH) 50.50.20

20 CALL OENS(1,TS.ZE.ZE*DSL,DSV,1)

IF (DS-DSL) 30.60.10

30 IF (DS-DSV) 50.60.10

40 KR=2

GO TO 80

50 KR=3

GO TO 80

REGION 1

60 KR=1

70 CALL PSS(S)

GO TO 90

REGIONS 2 AND 3

80 CALL OMLST(CS)

CALL OMLST2(TS)

PS=1000.*R*DS/TS*(1.*DS*(QCALC(TS)+DSQDT(DS,TS)))

90 P=PS*PCONV(KU)

RETURN

END
SUBROUTINE DENS(KU,T,P,O,DL,DV,KR)

--VERSION MARCH 1, 1972--

COMPUTE DENSITY D GIVEN TEMPERATURE T AND PRESSURE P.*
UNITS ARE SPECIFIED BY KU.* IF KR IS RETURNED OR
SPECIFIED AS 1, THE SATURATED LIQUID AND VAPOR DENSITIES,
DL AND DV RESPECTIVELY, ARE COMPUTED AS A FUNCTION
OF T OR P.* THE OTHER VALUE MUST BE INPUT AS 0.0.

COMMON /CHECK1/NI
COMMON /CONV1/DCONV(5)
COMMON/CONV2/TCONV(5)
COMMON/CONV3 /PCONV(5)
COMMON/ERROR/IROUT
COMMON /CRIT/ RHOCRT,PCRT,TCRT
COMMON /PSICON/ SIC1,SIC2,SIC3,SIC4,SIC5
COMMON /CONSTS/ TAU, RHOA,RHOB,TAUA,TAUB,R
COMMON/CHKS/OCHECK1,OCHECK2,OCHECK3,OCHECK4,OCHECK5
COMMON/CPPARMS/PCHECK1,PCHECK2,PCHECK3,PCHECK4,PCHECK5
COMMON/TPARAM/IS
COMMON /PRHOT/P0,DS,TT
EXTERNAL GSF,ODSF
IROUT=1
IF (KR.EQ.1) GO TO 70
TS=TCHECK(KU,KR,T)
TT = TS
CALL QMUST2(TS)
GO TO 5
70 IF (T.EQ.0.0) GO TO 75
PS=PCHECK(KU,KR,P)
TS=TS(PS)
TT = TS
IF (T.LE.0.) TT=TS*TCONV(KL)
CALL QMUST2(TS)
GO TO 5
75 TS = TCHECK (KU,KR,T)
TT = TS
CALL QMUST2(TS)
CALL PSSSI(PS)
IF (P.LE.0.) P=PS *PCONV(KU)

DETERMINE REGION

5 IF (KR-1) 10,80,10
10 PS=PCHECK(KU,KR,P)
IF (PS-PCH2)110,110,100
100 IF (TS-TCH2)130,130,120
120 KR=2
EST1 = 1.0455
EST2 = RHOCRT
TEST = 1000.*TS - 273.*15
IF ( TEST .GT. 100.) EST1 = 1.0107054
IF ( TEST .GT. 180.0) GO TO 121
IF (TEST .LE. 40.) TEST=40.*
EST2=(TEST*TEST*TEST*TEST*TEST*TEST*TEST*TEST*TEST*
1 +.54790571E-05+.6961325E-03+1.0220277E-09"
121 CALL RCRT (EST1,EST2,0.,CSF,CS)
GC TO 150
130 KR=3
EST=RHOCRT*3.
CALL ROOT(EST, DCH1, Q, CSF, DS)
GO TO 150
110 IF (TS - TCH2) 50, 50, 20
20 CALL PSSS(PSS)
   IF (ABS((PSS - PS) / PSS) - 1.0 - 4) 6(30, 30
30 IF (PS - PSS) 50, 60, 40
40 KR = 2
41 DS = .7147456
   IF (TS > 1.0) DS = .822368
   IF (TS > 1.947479) DS = .647456
   IF (TS > 2.0277805) DS = .907441
   IF (TS > 2.3086690) DS = .961538
   IF (TS > 2.6798874) DS = 1.001001
   IF (KR = EQ 1) GO TO 81
GO TO 90
50 KR = 3
   DS = PS * TS / (1000.0 * R)
GO TO 90
C
   REGION 1
C
60 KR = 1
80 CONTINUE
GO TO 41
81 CONTINUE
   DSL = SOLVE(DS, DSF, DSSF)
   DS = PS * TS / (1000.0 * R)
   IF (TCH2 / TS > 985) DS = .65 * RHOCRT
   IF (TCH2 / TS > 995) DS = .75 * RHOCRT
   IF (TCH2 / TS > 999) DS = .85 * RHCCRT
   IF (TCH2 / TS > 9995) DS = .90 * RHOCRT
   DSW = SOLVE(DS, DSF, DSSF)
   DL = DSL * DCONV(KU)
   DV = DSV * DCONV(KU)
RETURN
C
C   REGIONS 2 AND 3
C
90 DS = SOLVE(DS, DSF, DSSF)
150 D = DS * DCONV(KU)
RETURN
END
FUNCTION DSF(D)

FUNCTION USED TO SOLVE FOR DENSITY D GIVEN TEMPERATURE
AND PRESSURE

COMMON /CONSTS/ TAU_C, RHO_A, RHO_B, TAUA, E, R
COMMON /PRHCT/ PS, OS, TS
CALL QMLST(D)
PSTATE=1000.*R*D/(TS*(1.+D*(QCALC(TS)+D*DQDT(D,TS))))
DSF=PSTATE-PS
RETURN

ENTRY DSF(C)
CALL QMLST(D)
DSSF=1000.*R/TS*(1.+D*(2.0*QCALC(TS)+4.0*D*DQDT(D,TS)+D*DQ2D2T(D,TS)))
DSF=DSSF
RETURN
END
SUBROUTINE TEMP(KU,P,D,T,KR)

COMPUTE TAU=1000./TEMPERATURE IN USERS UNITS GIVEN PRESSURE AND DENSITY. IF KR IS SPECIFIED AS 1 TAU WILL BE A FUNCTION OF PRESSURE ONLY

COMMON /CONV2/TCNV(5)
COMMON/CHECKS/DCH1,DCH2,PCH1,PCH2,PCH3,TCH1,TCH2,TCH3,DST,TST,
HSCH1,HSCH2
COMMON/ERROR/IOUT
COMMON /PRHOTT/ PS,DS,TS
EXTERNAL TSF,DTSF
IOUT=3
PS=PCHECK(KU,KR,P)

DETERMINE REGION

IF (KR-1) 10,70,10
10 DS=DCHECK(KU,D)
   IF (PS-PCH2) 20,20,50
20 TS=TSS(PS)
   CALL DENS(1,TS,ZE,ZE,DSL,DSV,1)
   IF (DS-DSL) 30,60,40
30 IF (DS-DSV) 50,60,60
40 KR=2
   TS=TS+.01
   GO TO 80
50 KR=3
   TS=1.2
   GO TO 80

REGION 1

60 KR=1
   GO TO 110
70 TS=TSS(PS)
   GO TO 110

REGIONS 2 AND 3

80 CALL QMUST(DS)
   CALL QDT(DS,TS)
   CALL Q2DT(DS,TS)
   TS=SOLVE(TS,TSF,DTSF)

VERIFY REGION

IF (PS-PCH2)110,110,90
90 IF (TS-TCH2) 110,100,100
100 KR=2
110 T=TS*TCNV(KU)
RETURN
END
FUNCTION TSF(TS)  

--------VERSION MARCH 1,1972--------

FUNCTION USED TO SOLVE FOR TEMPERATURE TS GIVEN PRESSURE  

AND DENSITY

COMMON /PRHOTT/ PS,0,T
COMMON /CONSTS/ TAUC,RHOA,RHOB,TAUA,E,R
CALL QMUST2(TS)
PSSTATE=1000.0*R0 /TS*(1.0+(QCALC(TS)+D*QDTA(TS))))
TSF=PSSTATE-PS
RETURN

ENTRY TSF(TS)

CALL QMUST2(TS)

TSF=-TS*(1.0+D*D*QDTA(TS))
TSF=TSF*1000.0/(TS*TS)
RETURN
END

SUBROUTINE ENTH(KU,TT,D,H)

--------VERSION MARCH 1,1972--------

THIS ROUTINE COMPUTES ENTHALPY GIVEN THE TEMPERATURE PARAMETER TT  

AND THE DENSITY D.  I/O UNITS ARE SPECIFIED BY KU.

IF SATURATION VALUES ARE NEEDED, THIS ROUTINE MUST BE CALLED TWICE  

WITH DL AND DV INPUT AS D.

ENTHALPY IS RETURNED IN H.

COMMON/ERROR/IROUT  
COMMON/CCNV6/HCONV(S)
COMMON/SICOF / PSI1,PSI2,PSI3,PSI4,PSI5  
COMMON/CONSTS/ TAUC,RHOA,RHOB,TAUA,E,R  
IRON=4
TS=TCHECK(KU,KR,TT)
D=DCHECK(KU,D)
CALL QMUST(DS)
CALL QMUST2(TS)
T=1000.0/TS
PSI0= (PSI3*T+PSI2)*T+PSI1+(PSI4+PSI5*T)*ALOG(T)
PSIT=2.0*(PSI3*T+PSI2+PSI4/T+PSI5*(1.0+ALOG(T)))
H1= PSI0-T*PSIT
H2=1000.0*R/TS*(QCALC(TS)+TS*QTD(TS)+DS*QDT(DS,TS))
H=(H1+H2)*HCONV(KU)
RETURN
END

END
SUBROUTINE ENTI(KU, TT, D, S)

--VERSION MARCH 1, 1972------------------

THIS ROUTINE COMPUTES ENTROPY GIVEN THE TEMPERATURE PARAMETER TT
AND THE DENSITY D. I/O UNITS ARE SPECIFIED BY KU.

IF SATURATION VALUES ARE NEEDED, THIS ROUTINE MUST BE CALLED TWICE
WITH DL AND DV INPUT AS D.

ENTROPY IS RETURNED IN S.

COMMON/S:COF / PSI1, PSI2, PSI3, PSI4, PSI5
COMMON /CONSTS/ TAUC, RHOA, RHOB, TAU, E , R
COMMON/IERROR/IROUT
COMMON/CNV+/SCNV(S)
IROUT=5

TS=TCHECK(KU, KR, TT)
DS=DCHECK(KU, D)
CALL QMUST(DS)
CALL QMUST2(TS)
T=1000./TS
PSIT=2.*PSI3+T +PSI2+PSI4/T *PSI5*(1.-%LOG(T ))

SSS=%R*%LOG(DS)+DS%{QCALC(TS)-TS*QTD(TS))}-PSIT
S=SSS%SCNV(KU)

RETURN
END
SUBROUTINE TEMPPH(KU, P, H, T, D, DL, DV, KR)

COMMON /CONV1/OCONV(5)
COMMON /CONV2/TCONV(5)
COMMON/CCNV6/HCONV(5)
COMMON/PHCALL/PS, H, SS
COMMON/CHECKS/DCH1, DCH2, PCH1, PCH2, PCH3, TCH1, TCH2, TCH3, DST, TST,
1HSCH1, HSCH2
COMMON/IERROR/IROUT
EXTERNAL TSHF
PS=PCHECK(KU, KR, P)
IROUT=6
H$=P/HCONV(KU)
IF (HS-HSCH1) 20,10,10
10 IF (HS-HSCH2) 40,40,20
20 INPUT H - OUT OF RANGE TAG
WRITE(6,301) HS, HSCH1, HSCH2
301 FORMAT (10H0 INPUT H = ,G14.6, 29HJ/G IS OUT OF RANGE OF HMIN= 1 ,F4.1, 10Hand HMAX = ,F7.1, 3HJ/G )

C
40 IF (PS-PCH2) 140,140,130
130 TS1=TCH1
TS2=TCH3
GO TO 110
140 TS=0.0
CALL DENS(1, TS, PS, ZE, DL, DV, 1)
IF (KR=1) 50,70,90
50 CALL ENTH(1, TS, DL, HSL)
CALL ENTH(1, TS, DV, HSV)
IF (HS-HSL) 90,70,60
60 IF (HS-HSV) 70,70,100
C
REGION 1
C
70 KR=1
80 CALL DENS(1, TS, ZE, ZE, DSL, DSV, 1)
DL=DSL*OCONV(KU)
DV=DSV*OCONV(KU)
GO TO 120
C
REGION 2
C
90 KR=2
TS1=TCH3
PS=PS+1.00011
TS2=1000.0/(1000.0/TS-1.0E-5)
GO TO 110
C
REGION 3
C
100 KR=3
TS1=1000.0/(1000.0/TS+1.0E-5)
PS= PS*99988
TS2=TCH1
REGIONS 2 AND 3

CALL ROOTX(TS1,TS2,HS,TSHF,TS)
CALL DENS1(TS,PS,DS,ZE,ZE,KR)
D=DS*DCCNV(KU)

VERIFY REGION

IF (PS-PCH2) 120,120,150
IF (TS-TCH2) 170,170,160
GO TO 120
KR=3
T=TS*TCCNV(KU)
RETURN
END
SUBROUTINE TEMPPS (KUlPtStTIOeOL, DVtKR )

COMMON /CONV1/CCONV(5)
COMMON/CCNV4/ SCONV(5)
COMMON /CONV2/TCONV(5)
COMMON/PHCALL/PS,HS,SS
COMMON/CHECKS/DCH1,DCH2,PCH1,PCH2,PCH3,TCH1,TCH2,TCH3,DST,TST,
HSCH1,HSCH2
COMMON/ERROR/IERROR/IROUT
EXTERNAL TPSF
IROUT=7
S MAX=13.26
PS=PCHECK(KU,KR,P)
SS = S/SCONV(KU)
IF ( SS .LT. 0.0) GO TO 20
IF ( SS .LE. SMAX) GO TO 40

INPUT S - OUT OF RANGE TAG
WRITE(6,301) SS,SMAX
301 FORMAT (1OH,10H INPUT S = ,G14.6, 47H J/G-K IS OUT OF RANGE OF S min=0, 
10 AND SMAX= ,F7.1,5F7.1/G-K)
IF (PS-PCH2) 140,140,130
130 TS1=TCH1
TS2=TCH3
GO TO 110
140 TS=0.0
CALL DENS(1,TS,PS,ZE,DL,DV,1)
IF (KR=1) 50,70,50
50 CALL EN(1,TS,DL,SSL)
CALL EN(1,TS,DV,SSV)
IF ( SS-SSL ) 90,70,60
60 IF ( SS-SSV) 70,70,100

REGION 1

70 KR=1
80 CALL DENS(1,TS,PS,ZE,CSL,DV,1)
DL=DVL*DCONV(KU)
DV=DVS*DCONV(KU)
GO TO 120

REGION 2

90 KR=2
TS1=TCH3
PS=PS*1.00011
TS2=TS*1.00001
GO TO 110

REGION 3

100 KR=3
TS1=TS*99999
PS= PS*99988
TS2=TCH1
C REGIONS 2 AND 3
C
110 CALL ROOTX ( TS1, TS2, SS, TPSF, TS )
   CALL DENS1 (TS, PS, DS, ZE, ZE, KR)
   D = DS * DDCNV(KU)
C VERIFY REGION
C
   IF (PS - PCH2) 120, 120, 150
   150 IF (TS - TCH2) 170, 170, 160
   160 KR = 2
       GO TO 120
   170 KR = 3
   120 T = TS * TCCNV(KU)
       RETURN
       END

SIBFTC TSHF1
FUNCTION TSHF1(TS)
C
---------------VERSION MARCH 1, 1972------------------
COMMON/PHCALL/PS, HS, SS
   KR = 0
   CALL DENS1 (TS, PS, DS, ZE, ZE, KR)
   CALL FNT1 (TS, DS, HSC)
   TSHF = HSC
   RETURN
C
ENTRY TPSF(TS )
   KR = 0
   CALL DENS1 (TS, PS, DS, ZE, ZE, KR)
   CALL FNT1 (TS, DS, SSC)
   TPSF = SSC
   TSHF = TPSF
   RETURN
   FNC
SUBROUTINE CIPRL(I,KU,CP,CV,GAMMA,C)

THIS SUBROUTINE RETURNS THE FOLLOWING TO WASP IN USERS UNITS:

SPECIFIC HEAT AT CONSTANT PRESSURE  =CP

SPECIFIC HEAT AT CONSTANT VOLUME  =CV

SPECIFIC HEAT RATIO  =GAMMA

SONIC VELOCITY = C

THE PARTIALS PTV AND PDT EXPLAINED BELOW ARE RETURNED IN COMMON:

COMMON/COCPO/  COC1,COC2,COC3
COMMON/SICPO/  C1,C2,C3,C4,C5
COMMON /PARTLS/  PTV,PDT
COMMON /CONSTS/  TAU,RHOB,RH08,TAU,E,R
COMMON/CONV4/SCON(5)
COMMON/CONV5/CCONV(5)
COMMON/ERROR/IROUT

IROUT=8
TS=TCHECK(KU,KR,T)
TT=1000.*TS
DS=DCHECK(KU,O)

CALL QMST(DS)
CALL QMST2(TS)
CQ2T2D=Q2T2D(TS)
CQ(2CALC=QCALC(TS)
CQDI=QDI(DS,T)
CQTD=QTD(TS)
CQ2OT=Q2OT(DS,T)
CQ2OT=Q2OT(DS,T)

C--- PTV IS PARTIAL OF P BY T (NOT TAU)

PTV=R*DS*(1.0+DS*ICQCALC+DS*CQQT-TS*(CQTD+DS*CQ2DT))
PDT=R*T*(1.0+DS*(2.0*CQCALC+DS*(4.0*CQDT+DS*CQ2DT))

DHDT=-(2.0*C3TT+4.0/TT-C5*R*(1.0+DS*(CQCALC+DS*CQDT-TS*(DS*CQ2DT+
ICQTD+TS*CQ2DT)))

DHDD=R*(TT*CQCALC+1000.*CQTD+DS*(T*(3.0*CQDT+DS*CQ2DT)+1000.0*
ICQ2DT))

CP  = DHDT-DHDD*(PTV/PDT)

GAMMA=CP/CV

CP=CP*SCONV(KU)
C=CV*SCONV(KU)

GAMMAP=GAMMA  = 10.*POT

CS=0.0

IF (GAMMAP.GT.0.0) CS=1000.0*SQR(T(GAMMAP)

CTE=CCONV(KU)

RETURN
END
SUBROUTINE SURF(KU,KR,TIN,SURFT)

C          -------------------------------VERSION MARCH 1,1972-------------------

C          THIS ROUTINE CALCULATES THE SURFACE TENSION OF LIQUID WATER AND
C          THE LAPLACE CONSTANT

C
COMMON/IERROR/IROUT
COMMON/CCNV9/STCONV(5)
COMMON /LAPLAC/ ALC
DIMENSION A(5)
DIMENSION X(5)
DATA (A(I),I=1,5),B,TK /0.11609368 , 1.1214047 E-3, -5.7528052
1E-6, 1.2862746 E-6, -1.1497139 E-11, 0.83, 647.30 /

C---UNITS OF G = M/S**2
DATA G / 9.80665 /
IROUT=11

C---T IS DEG K
TAU=TCHECK(KU,KR,TIN)
T = 1000./TAU
MOLT=0.0
ALC=0.0
IF (T.GT.TK) RETURN
X(1)= TK-T
X(2)= X(1)*X(1)
X(3)= X(2)*X(1)
X(4)= X(3)*X(1)
X(5)= X(4)*X(1)
Y = (A(1)*X(2))/X(1)
DO 1 N=2,5
1 Y = Y+A(N) • X(N)
SURFT = Y

C--- UNITS OF SURFT MUST BE DYNE/CM
C--- UNITS OF ALC IS MM.
TR= T/647.30
IF (TR.GT. .998) GO TO 2
CALL DENS(KU,TAU,IE,ZE,DL,DV,1)
ALC = SQRT (SURFT/ (G•ABS (DL-DV)*1000. ) )

C---CONVERSION FACTOR FOR RESULTS TO BE IN MM AS IN THE TABLES
2 ALC = ALC * 31.622777
SURFT=SURFT*STCONV(KU)
RETURN
END
FUNCTION DTERM(XLM)

FUNCTION USED TO SOLVE EQ.(B52) FOR THERMAL CONDUCTIVITY

COMMON ITERAT/TR,T0,T1,T2,T3,T4,T5,T6,T7,T8
DOUBLR PRECI$ION T0,T1,T2,T3,T4,T5,T6,T7,T8
TCALC=(XLM*(XLM*(XLM*(XLM*(XLM*(XLM*(XLM*(XLM*(XLM*(XLM+T7)+T6)+T5)+T4)+T3)+
T2)+T1)*XLM+T0
DTERM=TCALC-TR
RETURN
ENTRY DDTH(XLM)

DERIVATIVE USED TO SOLVE EQ.(B52) IN NEWTON RAPHSON ITERATION

DDTH=(XLM*(XLM*(XLM*(XLM*(XLM*(XLM*(XLM*(XLM*(XLM*(XLM+T7)+T6)+T5)+
T4)*T4)*T4)*T3)+2*T2)*XLM+T1
DTERM=DDTH
RETURN
END
SUBROUTINE THERMI_UtKRtPINtT|NtDINtEXCESKeTCOND)

DATA ........ VERSION MARCH 1e1972 ........

SUBROUTINE CALCULATES THE THERMAL CONDUCTIVITY IN INTERNAL UNITS OF kW/m-K AND CONVERTS TO USERS UNITS.

EQUATIONS ARE THE INTERNATIONALLY AGREED UPON ONES IN REGIONS WHERE SAME ARE AVAILABLE AND ARE PROPOSED EQUATIONS IN OTHER REGIONS.

THE NEAR SUBCRITICAL REGION IS THE AUTHORS FIT.

COMMON/CCNVB/KCONV(5)
COMMON/IERROR/IROUT
COMMON/ITERAT/TR,T0,T1,T2,T3,T4,T5,T6,T7
REAL KCCNV
COMMON /CRIT/ RHOCRT,PCRT,TCRT
COMMON/ITPARAM/TAU
EXTERNAL OTHERPROC
DIMENSION CFC(5,2)
DATA CFC/-57861540,1.45746404, .17006978, .13348045, .32783991E-1, 1.70859254, .94131399, .62464434E-01, 1.85363188, 1.98065901/

DOUBLE PRECISION PROP
DOUBLE PRECISION AS(5),TBS(4),CS(4),SUM, SUM2
DATA AS/0.7384732, 0.44364636, 0.393669, 0.85363188, 0.98065901/

DOUBLE PRECISION AI0(2),B0(2),C10(3),D0(2),A,B,C,T1,T2,T3,T4,T5,T6,T7

DATA AI0/0.01012472978, .0514190083 /

DATA BI0 /663742.6916, 1.388806409, 1.388806409 /

DATA C10/338855.7874, 3.458000000, 13.63235390 /

DATA D10/-4.01002100200454, 23.94090099, 3.458000000, 13.63235390 /

DATA AI10/10.36535049, -4.513858027, .105213983, .12621383 /

DATA B110/-8.2350372, -1.55213983, -1.55213983 /

DATA C11 /0.1012472978, .0514190083 /, 810, 663742.6916, 1.388806409, .338855.7874, 576.8000000, .2060000000 /

DATA T1/T0,T1,T2,T3,T4,T5,T6,T7

DATA AB /1.36535049, -4.513858027, .105213983, .12621383 /

DATA B8 /1.514476538, -19.58487269, 113.6872874, 32.70035653 /

DATA T8 /397.3645617, 96.82356169, 703.0682926, 542.9942625, 101.2258396 /

DATA E9 /50.60225796, -105.677634, .55.96905687 /

CONVERT TAU AND PMN TO VARIOUS UNITS

IF (PBAR.LT. 1.0 .OR. PBAR.GT.500.) WRITE(6,151) TIN,PIN
IF (T.LT.0.0 .OR. T.GT.700.) WRITE(6,151) TIN,PIN
RETURNED THERMAL CONDUCTIVITY IS EXTRAPOLATED.

CHECK FOR REGION I

IF (T.LE.350..AND.DS.GT.RHOCRT) GO TO 100

CHECK FOR REGION I

IF (T.LE.350..AND.DS.GT.RHOCRT) GO TO 100

IF (T.LE.350..AND.DS.GT.RHOCRT) GO TO 100
CHECK FOR JAGGED LOWER BOUNDARY OF REGION II OR UPPER PART
OF REGION II

IF (PBAR.GT.450. AND T.LT.550.) GO TO 80
IF (PBAR.GT.350. AND T.LT.500.) GO TO 80
IF (PBAR.GT.275. AND T.LT.450.) GO TO 80
IF (PBAR.GT.225. AND T.LT.425.) GO TO 80
IF (PBAR.GT.175. AND T.LT.400.) GO TO 80

EQUATION (B40) FOR P=1.0 BARS

10 V1 = (17.6 * 0.0507*T + 0.00104*T*T - 4.51E-08*T*T*T)/1000.
IF (PBAR.GT.1.000) GO TO 20
TCOND=V1*KCONV(KU)
GO TO 500

EQUATION (B46) FOR REGION II.

20 ANS=((103.51 + 0.4198*T - 2.771E-05*T*T)*DS + 2.14821E+14/(T**4.2)*DS*DS
/1000 + V1)
TCOND=ANS*KCONV(KU)
GO TO 500

REGION I CALCULATIONS

100 CALL PSSS(PS)
PREDD = (PMN-PS)/PCRT
SUM1=((A5(5)*TR+A5(4))*TR+A5(3))*TR+A5(2)*TR+A5(1)
SUM2=(B5(4)*TR+B5(3))*TR+B5(2)*TR+B5(1)
SUM3=(C5(4)*TR+C5(3))*TR+C5(2)*TR+C5(1)
TCOND=(SUM1 + SUM3*PREDD + SUM2*PREDD)*KCONV(KU)
GO TO 500

CHECK FOR REGION III- USING BOUNDARY EQUATION (B54) WHICH DIVIDES
REGIONS III AND IV.

THEN SEPARATE HATCHED REGION WHERE NO EQUATION EXISTS FROM REMAINDER
OF REGION IV

80 IEQUA=10
IF(T.GT.450.) GO TO 300
PBOUND=E9(1)+E9(2)*TR+E9(3)*TR*TR
IF (PR.LT.PBOUND) GO TO 300
IF(TK.LT.TCRT.AND.DS.LT.RHOCRT) GO TO 400
IEQUA=8
GO TO 500

EQUATION (B52) IS SOLVED BY ITERATION

200 MTR=0
PRP=PR
CON=PRP-C8
T0 = A8(1) + CON*B8(1)
T1 = A8(2) + CON*B8(2)
T2 = A8(3) + CON*B8(3)
T3 = A8(4) + CON*B8(4)
T4 = A8(5) + CON*B8(5)
T5 = A8(6) + CON*B8(6)
T6 = A8(7) + CON*B8(7)
T7 = A8(8) + CON*B8(8)
T8 = A8(9) + CON*B8(9)

USE CONDUCTIVITY BASED ON BOUNDARY AS INITIAL ESTIMATE

P1 = PR
PR=PBOUND
GO TO 300
C THIS EQUATION DOES NOT ALWAYS CONVERGE NEAR THE BOUNDARY WHERE
IT SHOULD. SWITCH TO AUTHORS EXTRAPOLATION IF THIS HAPPENS.
C
IF (TCCND..LE.0.0) GO TO 400
GO TO 500
300 DCN=1.0D+0
B=(B1O(1) #PR**1.63) / (CON+B1O(2) #PR**3.26)
C= (C1O(1) #PR**1.5 + C1O(2)) / B - C1O(3)
CSP=C
TEST = DCN-B*D1O(1)/TR**7
Tl1=(A10(1)#PR+A1O(2))#TR**1.445/TEST**CSP
T22= D10(2)#PR**4 *EXP(-9.0#D1O(3)#(TR-1.0))/(D0N+D1O(4)
1 / #PR**12)
T33= D1O(5) - D1O(6) #PR *EXP(-D1O(3) * (TR-1.0))
ANS = T11 + T22*T33
IF (IEQUA. EQ. 8) GO TO 210
TCCND=ANS*KCONV(KU)
GO TO 500
C HATCHED REGION WHERE NO EQUATION EXISTS IN THE REFERENCES.
AUTHORS OWN EQ USED HERE WITH 1 BAR EQ.
400 V1= (17.6 +0.0587*T+.000104*T*T -4.51E-08*T*T*T)/1000.
XX= ALOG10(DS/RHOCRT)
KJ=1
IF (XX.GT.-39794) KJ=2
Y=CFC(1,KJ)+(CFC(5,KJ)*XX+CFC(4,KJ))XX+CFC(3,KJ)XX
1 +CFC(2,KJ)XX
TCCND=(10.**Y+V1)*KCONV(KU)
500 CONTINUE
C REACTING CONDUCTIVITY IN THE NEAR CRITICAL REGION BY SENGERS
C
DRHGC = ABS ( DS - RHOCRT ) / RHOCRT
DELABM=0.
IF (DRHGC.GT. .6) GO TO 520
DELTc = ABS ( TR-1. )
RAT= DS/RHOCRT
IF (DRHGC.LT.1.E-4) GC TO 510
IF (DELTc.LT.1.E-7) GO TO 502
XBETA = DELTC**.35/DRHOC
IF (XBETA.GT.9.4) GO TO 506
502 DELAMB= 11.6E-5 / (SQRT(RAT)*DRHGC**1.71)
GC TO 520
506 IF (XBETA.GT.3. ) GO TO 510
XB= ALOG10(XBETA)
ARAT= ((A4*X8+A3)*X8+A2)*X8+A1)*X8+A0
DELABM=11.6E-5/(SQRT(RAT)*DELTc**A6.)*10.**ARAT
GC TO 520
510 IF (DELTc.LT.1.E-7) GO TO 525
DELAMB = 11.6E-5/(SQRT(RAT)*DELTc**6)
520 EXCESK= DELAMB
RETURN
525 EXCESK =1.E30
RETURN
END
SUBROUTINE VISC(KU,KR,TIN,PIN,CIN,SVISC)

CALCULATE THE VISCOSITY GIVEN TAU,P, AND D IN USER'S UNITS KU.
ANSWER RETURNED IN USER-UNITS IN SVISC.*

COMMON/IERRK/IROLT
COMMON/CRT/RMCCAT,PCRT,TCRT
COMMON/TPARAM/TIN
COMMON/CCNV7/CCNV(5)

REAL MCGN
DIMENSION A(5),E(3),C(3),D(3),COF(5,2)
DATA (A(1),I=1,5) /241.4000,0.38282095,0.21628020,0.1498694,0.47116801 /
, ,
2 (B(I),I=1,3) /263.4511,0.4219836,80.4000 /
, ,
3 (C(I),I=1,3) /596.311587,1.204.75394,0.4219836 /
, ,
4 (D(I),I=1,3) /111.35647,67.320801,3.2051670 /
, ,
DATA COF/-6.4556581,1.3949436,30.259083,109.60682,15230031,-13.938,30.119832 /
, ,

!CTR=9

C-----
C----TK IS DEG K. T IS DEG C. TR IS REDUCED TEMP
TK=10000./TCHECK(KU,KR,TIN)
T = TK-273.15
TR=TK/TCRT

C-----P IS H/K. PMN IS MEGA NEWTONS/M*M. PR IS REDUCED PRESSURE
PMN=P/CHECK(KU,KR,PIN)
P = 10.0*PMN
PR=PMN/PCRT

C----- DD IS G/CC. SPVR IS REDUCED SPECIFIC VOLUME.
DD=DCHECK(KU,DIN)
SPVR=RHOCRT/DD

C CHECK FOR OUT OF RANGE ON P AND T
IF (P.LE.1.0) GO TO 100
IF (P.GT.800.0) WRITE(6,101) T,P
101 FORMAT(1H,*4H OUT OF RANGE. ANSWER IS EXTRAPOLATED FOR T=
1.F12.4, 4H P= ,F12.4)
IF (DD.GT.RHOCRT.AND.T.LT.300.) GO TO 100
GO TO 110

C

REGION I

100 X1 = 10.0*(*A(2)/(TR-A(3))
CALL PSS(PSS)
PSR=PSS/PCRT
X2 = 1.0 + (PR-PSR)*A(4)*(TR-A(5))
SVISC = (A(1)*X1*X2)/10.0*6*CCNV(KU)
RETURN

C

CALCULATE VISCOSITY FOR 1.0 BAR NEEDED FOR REGIONS II,III,IV

110 VISCI=(R(1))*(TR-R(2))*8(3)
IF (P.LE.1.0) GO TO 1000

C

CHECK FOR TEMPERATURE RANGE WHERE NO CURVE EXISTS
IF (T.GE.300.0.AND.T.LT.374.15) GO TO 400
IF (DD.GT.RHOCRT.AND.T.LT.300.) GO TO 200
GO TO 300
REGION II
--- FOR PRES -- 1 TO PSAT BAR AND 100 TO 300 CENT
200 SVISC = (VISC1 - 1.0/SPVR*(C(1) - C(2)*(TR-C(3))))/10.**6 * MCONV(KU)
RETURN

REGION III
--- FOR PRES -- 1 TO 800 BAR AND 375 TO 800 CENT
300 SVISC = (VISC1 + D(1)/SPVR + D(2)/(SPVR*SPVR) + D(3)/(SPVR*SPVR*SPVR))
10.**6 * MCONV(KU)
RETURN

AUTHORS EXTRAPOLATION USED FOR REGION IV
400 X=ALOG10(1./SPVR)
   KJ=1
   IF (X GT -.12493873) KJ=2
   Y= X*(X*(X*(X*COF(5,KJ)+COF(4,KJ))+COF(3,KJ))+COF(2,KJ))+COF(1,KJ)
   SVISC=(VISC1/1.E6+10.***(Y+1.)/.0152)*MCONV(KU)
RETURN
1000 SVISC=VISC1/10.**6*MCONV(KU)
RETURN
END
FLOW CHART FOR SUBROUTINE WASP

Note: KP is a binary sum, i.e., the addends are powers of 2, which are the individual KP options. Hence, each sum KP is obtained from a unique set of addends.
The following tables have been generated by WASP to facilitate comparing results to the ASME Tables (ref. 1) and the International Skeleton Tables (refs. 1 and 2). No attempt was made to reproduce the entire reference tables; only a select number of points were chosen at even intervals representative of the total range. The values in the following tables are in the same units and similar form as the reference tables. Results of comparisons between the calculated and the tabulated values are discussed in the main part of the text.

$\text{SIBFTC MTWASP}$

```
COMMON/PROPTY/KU,DL,DV,HL,HV,S,SL,SV,CV,CVL,TVV,CP,CPV,GAMMA,
GAMMAL,GAMMAY,C2,CVP,MU,MUL,MUV,K,KL,KV,SIGMA,EXCL,EXECV,EXCESK
DIMENSION PSIA(12),T1(11),VOL(12,11),HOUT(12,11),SOUT(12,11)
DIMENSION PBARTC(13),TOUT(20,13),TOUT2(31,13)
REAL MUX,MUL,MUV,K,KL,KV
DIMENSION T1(200),P(200),VL(200),HVOUT(200),SVOUT(200),HLOUT(200)
DIMENSION SOUT(200),VOUT(200)
DIMENSION PMEAR(12),TNEAR(6)
COMMON/LAPLAC/ALC
DIMENSION PCP(12),TCP(5),CPARY(12,5)
DIMENSION PBAR(7),TCENT(20),VOUT(20,7),PSVS(15),TFVS(31),VOUT2(31,
115)
```

```
MASTER TEST PROGRAM FOR WATER AND STEAM PROPERTY PACKAGE

PART 1

COMPARE SATURATION PROPERTIES OF ASME STEAM TABLES PAGES 83-88
AS A FUNCTION OF TEMPERATURE 35-705F IN INCREMENTS OF 10F

KU=3
NPT=1
T1=494.
10
KR=1
P1=0.0
CALL WASPII,L1,P1,RHO,H,KR)
T(NPT)=T1-460.
P(NPT)=P1
VL(NPT)=1./DL
VV(NPT)=1./DV
SOUT(NPT)=SL
SVOUT(NPT)=SV
HLOUT(NPT)=HL
HVOUT(NPT)=HV
```
NPT=NPT+1
T1=T1+12.0
IF (T1.LE.1165.) GO TO 10
NPT=NPT-1

C
C PRINT SATURATION RESULTS
WRITE(6,1)
1 FORMAT(1H1,51H COMPARABLE TO ASME TABLE NO. 1 PAGES 83-88)
WRITE(6,2)
WRITE(6,1)
WRITE(6,2)

2 FORMAT(1H0,90H T-F P-PSIA VL FT3/LBM VV HL BTU/L 1BM HV SL BTU/LBM-R SV)
3 FORMAT(1H F5.0,F10.4,2F12.6,2F12.3,2F12.4)
20 CONTINUE
WRITE(6,21)
21 FORMAT(1H1)

C
C PART 2 ASME TABLE NO. 3 PAGES 97-203
C
C PROPERTIES OF SUPERHEATED STEAM AND COMPRESSED WATER
TABLE IS 2 PAGES 32-750F AND 750-1500F
FOR EACH SET OF ISOBARS
WILL COMPARE 12 ISOBARS FOR VARIOUS TEMPERATURES

DATA PSIA/1.0,5.0,25.,100.,200.,500.,1000.,1500.,2000.,5000.,10000./
1.,14500./
DATA TF/32.,50.,100.,150.,300.,500.,700.,900.,1100.,1300.,1500./
DO 50 I=1,11
TIN=TF(I)+460.
DO 45 J=1,12
KR=0
KU=3
CALL WASP(1,3,TIN,PSIA(J),DI,H,KR)
IF (KR.EQ.1) GO TO 45
VOL(J,1)=1./D
HOUT(J,1)=H
SOUT(J,1)=S
45 CONTINUE
50 CONTINUE
WRITE(6,41)
WRITE(6,42)
DO 60 J=1,12,3
WRITE(6,44) PSIA(J),PSIA(J+1),PSIA(J+2)
DO 60 I=1,11
WRITE(6,43) TF(I),VOL(J,1),HOUT(J,1),SOUT(J,1),VOL(J+1,1),HOUT(J+1,1),SOUT(J+1,1)
41 FORMAT(1H1,20X,36H COMPARISON POINTS FOR TABLE NO. 3)
42 FORMAT(1H0,20X,47H (VOLUME,ENTHALPY,ENTROPY) FOR PRESSURE LISTED)
43 FORMAT(1H0,F6.0,F10.4,2F12.6,2F12.3,2F12.4)
44 FORMAT(1H0,6X,3(F10.0,4HPSIA,20X))
60 CONTINUE

C
C PART 3 ASME TABLE NO. 4 PAGES 208-220
C
C PROPERTIES OF SUPERHEATED STEAM AND COMPRESSED WATER IN
THE CRITICAL REGION
C
DATA PNEAR/2860.,3000.,3060.,3100.,3160.,3200.,3260.,3400.,3500.,
13600.,3800.,3960./
DATA TNEAR/650.,680.,710.,740.,770.,800. /
CC 80 I=1,6
TIN=TNEAR(I)+460.
CC 70 J=1,12
KR=0
CALL WASP(1,3,TIN,PNEAR(J),D,H,KR)
VCL(J,I)=1./D
IF (KR.EQ.1) GO TO 70
HCT(J,I)=H
SCUT(J,I)=S
70 CONTINUE
80 CONTINUE
WRITE(6,81)
81 FORMAT(1H1,20X,40H COMPARISON POINTS FOR ASME TABLE NO. 4 )
CC 90 J=1,12
WRITE(6,82)
82 FORMAT(1H1,20X,47H VOLUME,ENTHALPY,ENTROPY) FOR PRESSURE LISTED
WRITE(6,64)
PC(1,41)=PCP(J)
CC 90 I=1,6
WRITE(6,63) PCP(J),PCP(J+1),PCP(J+2)
CC 100 CONTINUE
C C PART 4 ASME TABLE NO. 9 PAGES 278-279
DATA PCP/1.,4.,10.,30.,60.,100.,200.,400.,1000.,3000.,6000.,10000. /
CC 109 CONTINUE
WRITE(6,69)
109 FORMAT(1H1,20X,42H COMPARISON POINTS FOR ASME TABLE NO. 9 )
WRITE(6,61)
111 FORMAT(1H1,4H 1PSIA,12(4X,F6.0)/1HQ,4HTEMP/,3H F /)
WRITE(6,62)
112 FORMAT(1H1,11H 1PCP)
CC 120 I=1,5
TIN=TCP(I)+460.
CC 110 J=1,12
KR=C
CALL WASP(1,4,TCP(J),D,H,KR)
CPARY(J,1)=CP
110 CONTINUE
WRITE(6,122) TCP(I),CPARY(J,1),J=1,12)
120 CONTINUE
112 FORMAT(1H1,F5.0,12F10.3)
C C PART 5 VISCOSITY CHECKOUT
DATA PBAR/1.,50.,200.,350.,500.,650.,800. /
12500.,10000.,12000. /
DATA TVFS/1500.,1450.,1400.,1350.,1300.,1250.,1200.,1150.,1100.
1150.,1100.,950.,900.,850.,800.,750.,700.,650.,600.,550.,500.,
2450.,400.,350.,300.,250.,200.,150.,100.,50.,32./
WRITE(6,500)
KL=1
CC 300 J=1,7
PIN=PBAR(J)/10.
CC 300 I=1,20
TIN=TCP(I)+460.
KR=C
CALL WASP(1,8,TIN,PIN,D,H,KR)
SCUT(J,1)=S
120 CONTINUE
WRITE(6,301)
301 FORMAT(1H1,42H VISCOSITY TABLE-INTERNATIONAL )
WRITE(6,302)
302 FORMAT(1H1,42H VISCOSITY TABLE-INTERNATIONAL )
WRITE(6,303)
303 FORMAT(1H1,42H VISCOSITY TABLE-INTERNATIONAL )
302 FORMAT(1HO,7(8X,F6.0,4HBARS ))
303 FORMAT(1HO,F5.0,7(F12.2,6X))
WRITE(6,500)
KU=3
CO 350 J=1,15
PIN=PSVS(J)
DO 350 I=1,31
TIN=TFVS(I)+460.0
KR=0
CALL WASP(I,8,TIN,PIN,D,H,KR)
IF (KR.EQ.1) GO TO 350
C THIS CONVERSION GETS FROM UNITS=3 OF PROGRAM TO UNITS OF TABLE
VOUT2(I,J)=MU*3.141592653589793/4.7880258
350 CONTINUE
WRITE(6,351)
WRITE(6,352) PSVS
DO 355 I=1,31
WRITE(6,353) TFVS(I),(VOUT2(I,J),J=1,15)
355 CONTINUE
351 FORMAT(1HO,45H VISCOSITY-ASME TABLE NO. 10 PAGE 280 )
352 FORMAT(1HO,5H PSIA,2X,15F8.2)
353 FORMAT(1H,2X,F15.2)
CONTINUE
354 FORMAT(IH1,B8H THERMAL CONDUCTIVITY - INTERNATIONAL BOOK
355 FORPAT(11HO,B5H-T-F )
356 FORMAT(IHO,FS°Ot13F9°2|
WRITE(6,357)
KU=3
CO 650 J=1,13
PIN=PSVS(J)
DO 650 I=1,31
TIN=TFVS(I)+660.0
KR=0
CALL WASP(I,16,TIN,PIN,D,H,KR)
IF (KR.EQ.1) GO TO 450
TCOUT2(I,J)=K*I.E3*3600.
650 CONTINUE
WRITE(6,651)
WRITE(6,652) PSVS(I),I=1,13
CO 455 I=1,31
455 FORMAT(6,353) TFVS(I),(TCOUT2(I,J),J=1,13)
456 FORMAT(IH1,45H THERMAL CONDUCTIVITY-ASME TABLE NO.11 PAGE 281 )
457 FORMAT(1HO,2X,F7.0/1HO,3HT-F )
458 FORMAT(1HO,13F9.2)
WRITE(6,459)
KU=3
CO 450 J=1,13
PIN=PSVS(J)
DO 450 I=1,31
TIN=TFVS(I)+460.0
KR=0
CALL WASP(I,16,TIN,PIN,D,H,KR)
IF (KR.EQ.1) GO TO 450
TCOUT2(I,J)=K*I.E3*3600.
450 CONTINUE
WRITE(6,451)
WRITE(6,452) PSVS(I),I=1,13
CO 455 I=1,31
455 FORMAT(6,353) TFVS(I),(TCOUT2(I,J),J=1,13)
456 FORMAT(IH1,45H THERMAL CONDUCTIVITY-ASME TABLE NO.11 PAGE 281 )
457 FORMAT(1HO,2X,F7.0/1HO,3HT-F )
458 FORMAT(1HO,13F9.2)
WRITE(6,459)
KU=3
CO 450 J=1,13
PIN=PSVS(J)
DO 450 I=1,31
TIN=TFVS(I)+460.0
KR=0
CALL WASP(I,16,TIN,PIN,D,H,KR)
IF (KR.EQ.1) GO TO 450
TCOUT2(I,J)=K*I.E3*3600.
450 CONTINUE
WRITE(6,451)
WRITE(6,452) PSVS(I),I=1,13
CO 455 I=1,31
455 FORMAT(6,353) TFVS(I),(TCOUT2(I,J),J=1,13)
456 FORMAT(IH1,45H THERMAL CONDUCTIVITY-ASME TABLE NO.11 PAGE 281 )
457 FORMAT(1HO,2X,F7.0/1HO,3HT-F )
458 FORMAT(1HO,13F9.2)
WRITE(6,459)
KU=3
CO 450 J=1,13
PIN=PSVS(J)
DO 450 I=1,31
TIN=TFVS(I)+460.0
KR=0
CALL WASP(I,16,TIN,PIN,D,H,KR)
IF (KR.EQ.1) GO TO 450
TCOUT2(I,J)=K*I.E3*3600.
450 CONTINUE
WRITE(6,451)
WRITE(6,452) PSVS(I),I=1,13
CO 455 I=1,31
455 FORMAT(6,353) TFVS(I),(TCOUT2(I,J),J=1,13)
456 FORMAT(IH1,45H THERMAL CONDUCTIVITY-ASME TABLE NO.11 PAGE 281 )
457 FORMAT(1HO,2X,F7.0/1HO,3HT-F )
458 FORMAT(1HO,13F9.2)
WRITE(6,459)
KU=3
CO 450 J=1,13
PIN=PSVS(J)
DO 450 I=1,31
TIN=TFVS(I)+460.0
KR=0
CALL WASP(I,16,TIN,PIN,D,H,KR)
IF (KR.EQ.1) GO TO 450
TCOUT2(I,J)=K*I.E3*3600.
450 CONTINUE
WRITE(6,451)
WRITE(6,452) PSVS(I),I=1,13
CO 455 I=1,31
455 FORMAT(6,353) TFVS(I),(TCOUT2(I,J),J=1,13)
456 FORMAT(IH1,45H THERMAL CONDUCTIVITY-ASME TABLE NO.11 PAGE 281 )
457 FORMAT(1HO,2X,F7.0/1HO,3HT-F )
458 FORMAT(1HO,13F9.2)
WRITE(6,459)
KU=3
CO 450 J=1,13
PIN=PSVS(J)
DO 450 I=1,31
TIN=TFVS(I)+460.0
KR=0
CALL WASP(I,16,TIN,PIN,D,H,KR)
IF (KR.EQ.1) GO TO 450
TCOUT2(I,J)=K*I.E3*3600.
450 CONTINUE
WRITE(6,451)
WRITE(6,452) PSVS(I),I=1,13
CO 455 I=1,31
455 FORMAT(6,353) TFVS(I),(TCOUT2(I,J),J=1,13)
456 FORMAT(IH1,45H THERMAL CONDUCTIVITY-ASME TABLE NO.11 PAGE 281 )
457 FORMAT(1HO,2X,F7.0/1HO,3HT-F )
458 FORMAT(1HO,13F9.2)
WRITE(6,459)
KU=3
CO 450 J=1,13
PIN=PSVS(J)
DO 450 I=1,31
TIN=TFVS(I)+460.0
KR=0
CALL WASP(I,16,TIN,PIN,D,H,KR)
IF (KR.EQ.1) GO TO 450
TCOUT2(I,J)=K*I.E3*3600.
450 CONTINUE
WRITE(6,451)
WRITE(6,452) PSVS(I),I=1,13
CO 455 I=1,31
455 FORMAT(6,353) TFVS(I),(TCOUT2(I,J),J=1,13)
456 FORMAT(IH1,45H THERMAL CONDUCTIVITY-ASME TABLE NO.11 PAGE 281 )
457 FORMAT(1HO,2X,F7.0/1HO,3HT-F )
458 FORMAT(1HO,13F9.2)
WRITE(6,459)
KU=3
CO 450 J=1,13
PIN=PSVS(J)
DO 450 I=1,31
TIN=TFVS(I)+460.0
KR=0
CALL WASP(I,16,TIN,PIN,D,H,KR)
IF (KR.EQ.1) GO TO 450
TCOUT2(I,J)=K*I.E3*3600.
450 CONTINUE
WRITE(6,451)
WRITE(6,452) PSVS(I),I=1,13
CO 455 I=1,31
455 FORMAT(6,353) TFVS(I),(TCOUT2(I,J),J=1,13)
456 FORMAT(IH1,45H THERMAL CONDUCTIVITY-ASME TABLE NO.11 PAGE 281 )
457 FORMAT(1HO,2X,F7.0/1HO,3HT-F )
458 FORMAT(1HO,13F9.2)
WRITE(6,459)
KU=3
CO 450 J=1,13
PIN=PSVS(J)
DO 450 I=1,31
TIN=TFVS(I)+460.0
KR=0
CALL WASP(I,16,TIN,PIN,D,H,KR)
IF (KR.EQ.1) GO TO 450
TCOUT2(I,J)=K*I.E3*3600.
DU 480  J=1,16               239
TI = TCENT(J)+273.15          240
CALL WASP(1,32, TI, PI, D, H, L)  241
480 WRITE(6,482) TCENT(J1), SIGMA, ALC   242
481 FORMAT(I1,H,20X,75H INTERNATIONAL BOOK -- TABLE NO.7, SURFACE TENS  243
ION AND LAPLACE CONSTANT /1H0,24H T-C DYN/CM MM /)       244
482 FORMAT(I1, F7.0, F8.2, F8.3 )      245
C
C END TEST PROGRAM               246
C
500 FORMAT(I1H1)                      248
STOP                                  249
END                              250
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<th>Saturated vapor, ft³/lbm</th>
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<th>Entropy, Btu/(lbm)°R</th>
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**Note:** The table continues with similar entries for temperatures from 0 to 50°F.
## COMPARISON POINTS FOR ASME TABLE 3, REF. 1

(VOLUME, ENTHALPY, ENTROPY FOR PRESSURE LISTED)

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(VOLUME, ENTHALPY, ENTRPY FOR PRESSURE LISTED)

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(VOLUME, ENTHALPY, ENTRPY FOR PRESSURE LISTED)

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(VOLUME, ENTHALPY, ENTRPY FOR PRESSURE LISTED)

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(VOLUME, ENTHALPY, ENTRPY FOR PRESSURE LISTED)
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Comparison points for ASME Table 9, Ref. 1

(Specific heat, $C_p$, Btu/(lbm)°F)
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**COMPARISON POINTS FOR ASME TABLE 11, Ref. 1**

(THERMAL CONDUCTIVITY, \(10^{-3}\) Btu/(lbm)(ft)(\(^\circ\)F))
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APPENDIX G

METASTABLE SUBROUTINE (PMETAS)

Although property measurements for other than stable states are very difficult to make, metastable states are of interest in heat-transfer and fluid-flow calculations. The fundamental equation

\[ \psi = \psi_0(T) + RT[\ln \rho + \rho Q(\rho, \tau)] \]

represents a continuum of single-phase states between the saturated liquid and saturated vapor states which can be classified as either metastable or unstable (as for the Van der Waals equation). Consequently, properties of the superheated liquid and supersaturated vapor can be determined. It is pointed out in reference 3 that between 300°C and the critical temperature, the nonstable states as determined by the fundamental equation have a single maximum and minimum. At lower temperatures, more than one pair of extremum exists for which the authors of reference 3 attach no significance.

The subroutine PMETAS (KU, T, D, P, KR) is provided to illustrate to the user of WASP how the metastable and unstable states can be determined. Given a density D and a temperature T (KU and KR have their usual meanings) the pressure P is returned

\[ P = \rho RT \left[ 1 + \rho Q(\rho, \tau) + \rho^2 \frac{\partial Q(\rho, \tau)}{\partial \rho} \right] \]

The user can then formulate a locus of maximum and minimum points, as for the Van der Waals equation, and determine if the point is stable, metastable, or unstable. (Note that PMETAS will also return stable points provided D and T represent a stable point.) Examples of the metastable and unstable loci are given as figures 14.
SUBROUTINE PMETAS(KU,T,C,P,KR)

THIS ROUTINE CALCULATES PRESSURE FOR ANY T INPUT AND D INPUT. THIS ROUTINE DOES NOT DEFINE A REGION AND IS NOT CALLED BY -WASP-. THE USER CALLS IT DIRECTLY AND IT CAN BE USED IN THE METASTABLE STATE.

COMMON /CONV3/PCCNV(S)
COMMON /TPARAM/TS
COMMON /CONSTS/TAUC,RHCA,RHOB,TAUAA,E,R
COMMON /CHECKS/CH1,CH2,PCH1,PCH2,PCH3,TCH1,TCH2,TCH3,DST,TST,
HSCH1,HSCH2
COMMON /ERROR/IRCUT
DS=DCHECK(KU,D)
TS=TCHECK(KU,KR,T)

ONE EQUATION FOR ALL REGIONS

CALL QMUST(DS)
CALL QMUST2(TS)
PS=1COO.*R*DS/TS*(1.+DS*(QCALC(TS)+DS*QDT(DS,TS)))
P=PS*PCCNV(KU)
RETURN
END

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APPENDIX H

THERMODYNAMIC RELATIONS AND DERIVATIVES

The symbols $C_p$, $C_v$, $H$, $P$, $R$, $S$, $T$, and $\rho$ have the same meaning as defined elsewhere in this report. The other symbols used exclusively in this appendix are defined as follows:

$A = E - TS$  Helmholtz free energy or work content

$E$  internal energy

$F = H - TS$  Gibbs free energy or free energy

$K$  equilibrium constant

$V$  specific volume

To illustrate the facility of the partial derivatives, Roder and Weber (ref. 17) give five which are useful to engineers:

Specific heat input:

$$V \left( \frac{\partial H}{\partial V} \right)_P = \rho C_p \left[ \frac{\partial P}{\partial T} \right]_T$$

Energy derivative:

$$V \left( \frac{\partial P}{\partial E} \right)_V = \frac{1}{\rho C_v} \left( \frac{\partial P}{\partial T} \right)_\rho$$

Isothermal bulk modulus:

$$V \left( \frac{\partial P}{\partial V} \right)_T = - \rho \left( \frac{\partial P}{\partial \rho} \right)_T$$
Volume expansivity:

\[ \frac{1}{V} \frac{\partial V}{\partial T} \bigg|_P = \rho \frac{\partial P}{\partial T} \bigg|_P \]

The background material necessary to derive these and other parameters as the Joule-Thomson coefficient

\[ \mu = \frac{1}{\rho C_p} \left[ \frac{\partial P}{\partial T} \bigg|_P \rho - 1 \right] \]

can be found in most thermodynamic texts.

WASP provides the partial derivatives \((\partial P/\partial \rho)_T\) and \((\partial P/\partial T)_\rho\). With the aid of the following thermodynamic derivatives and the Bridgeman Tables, any thermodynamic parameter can be found. The following thermodynamic tables were taken from reference 18.

Differential energy formulas:

\[ dE = T \, dS - P \, dV \]
\[ dH = T \, dS + V \, dP \]
\[ dA = -S \, dT - P \, dV \]
\[ dF = -S \, dT + V \, dP \]

Maxwell relations:

\[ \left( \frac{\partial T}{\partial V} \right)_S = - \left( \frac{\partial P}{\partial S} \right)_V \]
\[ \left( \frac{\partial T}{\partial P} \right)_S = \left( \frac{\partial V}{\partial S} \right)_P \]
\[
\frac{\partial S}{\partial V}_T = \frac{\partial P}{\partial T}_V
\]

\[
\frac{\partial S}{\partial P}_T = -\frac{\partial V}{\partial T}_P
\]

**Energy-function derivatives:**

\[
\frac{\partial E}{\partial S}_V = \frac{\partial H}{\partial S}_P = T
\]

\[
\frac{\partial E}{\partial V}_S = \frac{\partial A}{\partial V}_T = -P
\]

\[
\frac{\partial H}{\partial P}_S = \frac{\partial F}{\partial P}_T = V
\]

\[
\frac{\partial F}{\partial T}_P = \frac{\partial A}{\partial T}_V = -S
\]

**Heat-capacity relations:**

\[
C_V = \frac{\partial E}{\partial T}_V = T\frac{\partial S}{\partial T}_V
\]

\[
C_P = \frac{\partial H}{\partial T}_P = T\frac{\partial S}{\partial T}_P
\]

\[
C_P - C_V = -T\left(\frac{\partial V}{\partial T}_P\right)^2\frac{\partial P}{\partial V}_T
\]

\[
C_P - C_{\text{sat}} = T\frac{\partial V}{\partial T}_P\frac{\partial P}{\partial T}_{\text{sat}}
\]

\[
\frac{\partial C_V}{\partial V}_T = T\frac{\partial^2 P}{\partial T^2}_V
\]
\[
\frac{\partial C_P}{\partial P} \bigg|_T = -T \frac{\partial^2 V}{\partial T^2} \bigg|_P
\]

Effect of \( P \) or \( V \) on \( H \) or \( E \):

\[
\frac{\partial H}{\partial P} \bigg|_T = V - T \frac{\partial V}{\partial T} \bigg|_P \\
\frac{\partial E}{\partial V} \bigg|_T = T \frac{\partial P}{\partial T} - P
\]

Temperature effect on \( \Delta F/T = -R \ln K \):

\[
\text{\bf{\left[ \frac{\partial (\Delta F)}{\partial T} \right]}}_P = -R \frac{\partial \ln K}{\partial T} = -\Delta H \frac{1}{T^2}
\]

Partial molal quantities, where \( Y \) is any extensive quantity:

\[
\bar{y}_1 = \left( \frac{\partial Y}{\partial n_1} \right) \bigg|_{P, T, n_2, n_3, \ldots}
\]

\( Y = n_1 \bar{y}_1 + n_2 \bar{y}_2 + \ldots \)

\[
x_1 \left( \frac{\partial \bar{y}_1}{\partial x_1} \right) + x_2 \left( \frac{\partial \bar{y}_2}{\partial x_1} \right) + \ldots = 0
\]

\[
\left( \frac{\partial \bar{y}_1}{\partial n_1} \right) = \frac{\partial^2 Y}{\partial n_1 \partial n_j} = \left( \frac{\partial y_i}{\partial n_j} \right)
\]
The so-called Bridgeman Tables are summarized as follows:

\[(\partial T)_P = -(\partial P)_T = 1\]

\[(\partial V)_P = -(\partial P)_V = \frac{(\partial V)}{(\partial T)_P} \]

\[(\partial S)_P = -(\partial P)_S = \frac{C_P}{T}\]

\[(\partial E)_P = -(\partial P)_E = C_P - P\frac{(\partial V)}{(\partial T)_P}\]

\[(\partial H)_P = -(\partial P)_H = C_P\]

\[(\partial F)_P = -(\partial P)_F = -S\]

\[(\partial A)_P = -(\partial P)_A = \left[ S + P\frac{(\partial V)}{(\partial T)_P} \right]\]

\[(\partial V)_T = -(\partial T)_V = \frac{(\partial V)}{(\partial P)_T}\]

\[(\partial S)_T = -(\partial T)_S = \frac{(\partial V)}{(\partial T)_P}\]

\[(\partial E)_T = -(\partial T)_E = T\frac{(\partial V)}{(\partial T)_P} + P\frac{(\partial V)}{(\partial P)_T}\]

\[(\partial H)_T = -(\partial T)_H = -V + T\frac{(\partial V)}{(\partial T)_P}\]

\[(\partial F)_T = -(\partial T)_F = -V\]

\[(\partial A)_T = -(\partial T)_A = P\frac{(\partial V)}{(\partial P)_T}\]
\[(\partial S)_V = - (\partial V)_S = \frac{1}{T} \left[ C_P \left( \frac{\partial V}{\partial P}_T \right) + T \left( \frac{\partial V}{\partial T}_P \right)^2 \right] \]

\[(\partial E)_V = - (\partial V)_E = C_P \left( \frac{\partial V}{\partial P}_T \right) + T \left( \frac{\partial V}{\partial T}_P \right)^2 \]

\[(\partial H)_V = - (\partial V)_H = C_P \left( \frac{\partial V}{\partial P}_T \right) + T \left( \frac{\partial V}{\partial T}_P \right)^2 - V \left( \frac{\partial V}{\partial T}_P \right) \]

\[(\partial F)_V = - (\partial V)_F = - \left[ V \left( \frac{\partial V}{\partial T}_P \right) + S \left( \frac{\partial V}{\partial P}_T \right) \right] \]

\[(\partial A)_V = - (\partial V)_A = - S \left( \frac{\partial V}{\partial P}_T \right) \]

\[(\partial E)_S = - (\partial V)_E = \frac{P}{T} \left[ C_P \left( \frac{\partial V}{\partial P}_T \right) + T \left( \frac{\partial V}{\partial T}_P \right)^2 \right] \]

\[(\partial H)_S = - (\partial S)_H = - \frac{V C_P}{T} \]

\[(\partial F)_S = - (\partial S)_F = - \frac{1}{T} \left[ V C_P - ST \left( \frac{\partial V}{\partial T}_P \right) \right] \]

\[(\partial A)_S = - (\partial S)_A = \frac{1}{T} \left\{ P \left[ C_P \left( \frac{\partial V}{\partial P}_T \right) + T \left( \frac{\partial V}{\partial T}_P \right)^2 \right] + ST \left( \frac{\partial V}{\partial T}_P \right) \right\} \]

\[(\partial H)_E = - (\partial E)_H = - V \left[ C_P - P \left( \frac{\partial V}{\partial T}_P \right) \right] - P \left[ C_P \left( \frac{\partial V}{\partial P}_T \right) + T \left( \frac{\partial V}{\partial T}_P \right)^2 \right] \]

\[(\partial F)_E = - (\partial E)_F = - V \left[ C_P - P \left( \frac{\partial V}{\partial T}_P \right) \right] + S \left[ T \left( \frac{\partial V}{\partial T}_P \right) + P \left( \frac{\partial V}{\partial P}_T \right) \right] \]

\[(\partial A)_E = - (\partial E)_A = P \left[ \left( C_P + S \right) \left( \frac{\partial V}{\partial P}_T \right) + T \left( \frac{\partial V}{\partial T}_P \right)^2 \right] + ST \left( \frac{\partial V}{\partial T}_P \right) \]
\[
(\partial F)_H = -(\partial H)_F = -V(C_p + S) + TS\left(\frac{\partial V}{\partial T}\right)_P
\]

\[
(\partial A)_H = -(\partial H)_A = -\left[ S + P\left(\frac{\partial V}{\partial T}\right)_P \right] \left[ V - T\left(\frac{\partial V}{\partial T}\right)_P \right] + PC_P\left(\frac{\partial V}{\partial P}\right)_T
\]

\[
(\partial A)_F = -(\partial F)_A = -S \left[ V + P\left(\frac{\partial V}{\partial P}\right)_T \right] - PV\left(\frac{\partial V}{\partial T}\right)_P
\]
REFERENCES


### TABLE I. - OPERATIONS SHEET FOR SUBROUTINE WASP

| REAL MU, MUL, MUV, K, KL, KV |

#### CALL WASP (KS, KP, T, P, E, H, KR)

| Region | KR=0 Unknown, check KR returned |
| KR=1 Saturation |
| KR=2 Liquid |
| KR=3 Gas and/or fluid |
| Enthalpy, J/g |
| Density, g/cm³ |
| Pressure, MN/m² |
| Temperature, K |

#### Thermodynamic and transport properties

- **KP=0**: Only P, ρ, and T returned
- **KP=1**: H Enthalpy, J/g; (H), (HL), (HV)
- **KP=2**: S Entropy, J/(g)(K); (S), (SL), (SV)
- **KP=4**: Cᵥ Specific heat at constant volume, J/(g)(K); (CV), (CVL), (CW)
- **KP=5**: Cₚ Specific heat at constant pressure, J/(g)(K); (CP), (CPL), (CPV)
- **KP=6**: υ Ratio of specific heats, Cᵥ/Cₚ; (GAMMA), (GAMMAL), (GAMMAV)
- **KP=7**: c Sonic velocity, cm/sec; (C), (CL), (CVP)
- **KP=8**: µ Dynamic viscosity, g/(cm)(sec); (MU), (MUL), (MUV)
- **KP=16**: k Thermal conductivity, W/(cm)(K); (K), (KL), (KV)
- **KP=32**: σ Surface tension, dyne/cm; (SIGMA)

#### Input specification of independent properties

- **KS=1**: ρ = f(T, P); given T, P find ρ
- **KS=2**: P = f(T, ρ); given T, ρ find P
- **KS=3**: T = f(P, ρ); given P, ρ find T
- **KS=4**: T, ρ = f(P, H); given P, H find T, ρ
- **KS=5**: T, ρ = f(P, S); given P, S find T, ρ

#### Notes:

1. The units indicator, KU, must be set such that 1 ≤ KU ≤ 5 or no valid property values can be determined. See table II.
2. Reset KR ≠ 1 for each call to WASP to be assured of nonsaturation calculations (unless T = T_{sat} and P = P_{sat}).
3. Sample problem:

   **COMMON, PROPY/ KU, etc. (as above)**
   **REAL MU, etc. (as above)**
   **KU=1**
   **KR=0**
   **T=773.0**
   **D=0.178**

   **Call WASP (2, 31, T, P, D, H, KR)**

   WASP will return P = 40. MN/m², KR = 3, H = 2902.4, and the following values in COMMON: S = 5.4689, CV = 2.4503, CP = 5.7893, GAMMA = 2.363, C = 57415.4, MU = 0.3682x10⁻³, K = 0.1534x10⁻².

#### KP input is Σ KP options if more than one property is requested. For example, if enthalpy and entropy are desired, set KP equal to 3.


<table>
<thead>
<tr>
<th>Physical quantity</th>
<th>Units specification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>KU=1</td>
</tr>
<tr>
<td>Temperature</td>
<td>K</td>
</tr>
<tr>
<td>Density</td>
<td>g/cm³</td>
</tr>
<tr>
<td>Pressure</td>
<td>MN/m²</td>
</tr>
<tr>
<td>Enthalpy</td>
<td>joule/g</td>
</tr>
<tr>
<td>Entropy, specific heat</td>
<td>cm/sec</td>
</tr>
<tr>
<td>Sonic velocity</td>
<td>g/(cm)(sec)</td>
</tr>
<tr>
<td>Dynamic viscosity</td>
<td>joule/(cm)(sec)(K)</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>dyne/cm</td>
</tr>
<tr>
<td>Surface tension</td>
<td></td>
</tr>
</tbody>
</table>

aKU=4, 5 permit the user to work in other units; however, the proper conversions must be entered into BLOCK DATA. To add special set of units for KU=4 or KU=5:

1. User's program must contain following COMMON
   /CONV1/DCONV(5)
   /CONV2/TCONV(5)
   /CONV3/PCONV(5)
   /CONV4/SCONV(5)
   /CONV5/CCONV(5)
   /CONV6/HCONV(5)
   /CONV7/MCONV(5)
   /CONV8/KCONV(5)
   /CONV9/STCONV(5)
   REAL MCONV, KCONV

   or modify BLOCK DATA subprogram directly
   (See appendix E for listing of BLOCK DATA.)

2. Store conversion factors in fourth and/or fifth position of each array such that (D in input unit desired)/DCONV(4) = g/cm³, etc. All conversion factors must change input to units of KU=1. For output then, (D in g/cm³) x DCONV(4) = (D in desired units).
The subroutines in WASP may be loaded in any order with respect to the user's program. To run successfully, there must appear in at least one user subroutine the following:

1. COMMON/PROPTY/, etc.
   REAL MU, etc.
2. KU=1 (or 2, 3, 4, 5)
3. Other input variable specifications
4. Calls to subroutine WASP

The COMMON/PROPTY/, of course, must be in the main program or subroutine where the user expects answers to be returned from WASP. It could be in several or all user subroutines.
### TABLE IV. - COEFFICIENTS OF Q-FUNCTION, $\psi_0$-FUNCTION, AND VAPOR PRESSURE CURVE

(a) Coefficients of Q-function

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>29.492937</td>
<td>-5.1985860</td>
<td>6.8335354</td>
<td>-0.1564104</td>
<td>-6.3972405</td>
<td>-3.9661401</td>
<td>-0.69048554</td>
</tr>
<tr>
<td>2</td>
<td>-132.13917</td>
<td>7.7779182</td>
<td>-26.149751</td>
<td>0.72546108</td>
<td>26.409282</td>
<td>15.453061</td>
<td>2.7407416</td>
</tr>
<tr>
<td>3</td>
<td>274.64632</td>
<td>-33.301902</td>
<td>65.326396</td>
<td>-9.2734289</td>
<td>-17.407437</td>
<td>-5.1247070</td>
<td>-5.1028070</td>
</tr>
<tr>
<td>5</td>
<td>342.18431</td>
<td>-177.31074</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>-244.50042</td>
<td>127.48742</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>7</td>
<td>155.18535</td>
<td>137.46153</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>5.9728487</td>
<td>155.97836</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>-410.30848</td>
<td>337.31180</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>-416.05860</td>
<td>-209.88866</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

(b) Coefficients of $\psi_0$-function

<table>
<thead>
<tr>
<th>i</th>
<th>Coefficients $C_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1855.3865</td>
</tr>
<tr>
<td>2</td>
<td>3.278642</td>
</tr>
<tr>
<td>3</td>
<td>-0.0037903</td>
</tr>
<tr>
<td>4</td>
<td>46.174</td>
</tr>
<tr>
<td>5</td>
<td>-1.02117</td>
</tr>
</tbody>
</table>

(c) Coefficients of vapor pressure curve

<table>
<thead>
<tr>
<th>i</th>
<th>Coefficients $D_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.9304370</td>
</tr>
<tr>
<td>2</td>
<td>-2309.5789</td>
</tr>
<tr>
<td>3</td>
<td>.34522497×10⁻¹</td>
</tr>
<tr>
<td>4</td>
<td>-.13621289×10⁻³</td>
</tr>
<tr>
<td>5</td>
<td>.25878044×10⁻⁶</td>
</tr>
<tr>
<td>6</td>
<td>-.24709162×10⁻⁹</td>
</tr>
<tr>
<td>7</td>
<td>.95937646×10⁻¹³</td>
</tr>
</tbody>
</table>
### TABLE V. - NECESSARY AND OPTIONAL ROUTINES

(a) Necessary routines

<table>
<thead>
<tr>
<th>NAME (* indicates multiple entry)</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLOCK DATA</td>
<td>Stores coefficients for the fundamental equation</td>
</tr>
<tr>
<td>*(CHECK, TCHECK, PCHECK, DCHECK)</td>
<td>Performs region and limit checks for all subroutines; converts user's units to internal program units</td>
</tr>
<tr>
<td>ROOT</td>
<td>Mathematical routines used in all iterative solutions necessary to calculation of properties</td>
</tr>
<tr>
<td>ROOTX</td>
<td></td>
</tr>
<tr>
<td>SOLVE</td>
<td></td>
</tr>
<tr>
<td>QCALC *(Qmust, Qmust2)</td>
<td>Q-function and derivatives used in equation-of-state calculations (See equations used by all KS and KP options.)</td>
</tr>
<tr>
<td>QTD</td>
<td></td>
</tr>
<tr>
<td>Q2T2D *(Q2DTA, Q2DT) *(Q2D2TA, Q2D2T)</td>
<td></td>
</tr>
<tr>
<td>DENS</td>
<td>Used for KS=1 request and to determine region number for most other KS and KP options</td>
</tr>
<tr>
<td>PSSS *(DSSF, DDSF)</td>
<td></td>
</tr>
</tbody>
</table>

(b) Optional routines

<table>
<thead>
<tr>
<th>NAME (* indicates multiple entry)</th>
<th>KS or KP option involved</th>
<th>Statement numbers in subroutine WASP</th>
<th>Additional conditions for removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRESS</td>
<td>KS=2</td>
<td>20</td>
<td>None</td>
</tr>
<tr>
<td>TEMP TSS *(TSSF, DTSSF) *(TSF, DTSF)</td>
<td>KS=3 (also KS=4 and KS=5)</td>
<td>30 40 45</td>
<td>Must also remove TEMPPH, TEMPPPS, TSHF, and TPSF</td>
</tr>
<tr>
<td>TEMPPPH *(TSHF, TPSF)</td>
<td>KS=4</td>
<td>40</td>
<td>None</td>
</tr>
<tr>
<td>TEMPPPS *(TSHF, TPSF)</td>
<td>KS=5</td>
<td>45</td>
<td>None</td>
</tr>
<tr>
<td>ENTH KP=1 (also KS=4)</td>
<td>60 40</td>
<td>Must also remove TEMPPH and TSHF</td>
<td></td>
</tr>
<tr>
<td>ENT KP=2 KS=5</td>
<td>100 45</td>
<td>Must also remove TEMPPS and TPSF</td>
<td></td>
</tr>
<tr>
<td>CPPRL KP=4</td>
<td>130 to 140</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>VISC KP=8</td>
<td>160 to 170</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>THERM KP=16</td>
<td>180 to 190</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>SURF KP=32</td>
<td>240</td>
<td>None</td>
<td></td>
</tr>
</tbody>
</table>
Figure 1 - Excess viscosity as function of reduced density for region $563 \text{ K} \leq T \leq 673 \text{ K}$. 

Region 1: 
- Region represented by *data* points on this figure
- Region where no fit is available (region 4)

Region 2:
- $360^\circ \text{ C}$, $18,675 \text{ MN/m}^2$
- $350^\circ \text{ C}$, $16,535 \text{ MN/m}^2$
- $339^\circ \text{ C}$, $12,86 \text{ MN/m}^2$
- $320^\circ \text{ C}$, $11,289 \text{ MN/m}^2$
- $310^\circ \text{ C}$, $9,07 \text{ MN/m}^2$

Pressure, $P$, \text{MN/m}^2
- Data from ref. 2.

Curves from program WASP
- Vapor
- Liquid

Saturation locus

Reduced density, $\rho/\rho_c$
Figure 2. - Excess thermal conductivity as function of reduced density for region $603 \, K \leq T \leq 673 \, K$. 

Pressure, $P$, MN/m$^2$ 
(Data from ref. 2.)

- 35
- 30
- 25
- 20
- 15
- 10
- 5
- 2.5
- 1

- Vapor
- Liquid
- Saturation locus
- Curve from program WASP
Figure 3. Density as a function of temperature for selected isobars.
Figure 4. - Pressure and the derivative \( \frac{\partial P}{\partial T} \) as function of temperature for selected isochores.
Figure 5. Pressure as function of specific volume for selected isotherms.

Figure 6. Enthalpy as function of temperature for selected isobars.
Figure 7. - Entropy as function of temperature for selected isobars.

Figure 8. - Specific heat at constant pressure as function of temperature for selected isobars.
Figure 9. - Specific heat at constant volume and specific-heat ratio \( \frac{C_p}{C_v} \) as function of temperature for selected isobars.
Figure 12. - Thermal conductivity as function of temperature for selected isobars and total thermal conductivity as function of density ratio for selected isotherms.

(a) Thermal conductivity as function of temperature for selected isobars.

(b) Approximation to anomalous behavior of thermal conductivity for water in the near-critical thermodynamic state.
Figure 13. - Surface tension and Laplace constant as function of temperature.
Figure 14. Pressure-volume relations for metastable region along selected isotherms.
Figure 17. Temperature differences as function of temperature. Comparison of WASP calculated PVT to International Skeleton Tables.